Supply and exhaust ventilation with heat and moisture recovery

Energy use for different solutions and scenarios

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Supply and exhaust ventilation with heat and moisture recovery – energy use for different solutions and scenarios

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FORMAS

Abstract

Theory and experience exist for much of the components of a combined system with heat recovery ventilation, building and occupant, but the parts are not put together in a comprehensive and analytical way to let the building sector take part of developed and positivistic knowledge that is needed to make predictable and desired dwellings. This project will, together with numerous ongoing projects, address the lack of models and tools for analyzing the combination of ventilation system, building and occupant from a moisture, energy and indoor environmental perspective. The result from the project us a model and a tool to use for industry, as well as guidelines, conclusions on function and optimization of residential heat recovery ventilation for future sustainable housing.

Content

1. Introduction

Residential homes in Europe use about a third of Europe's total energy use (Eurostat, 2022). The heating of the ventilation air is a substantial part of this, varying depending on the performance of the building. An efficient solution to lower energy costs is to install a mechanical supply and extract ventilation systems with heat or energy recovery. Installation of such systems are therefore becoming more and more common in residential buildings. Typical performance of heat recovery in residential ventilation systems shows temperature efficiencies of approximately 80 % and above, which means that there is an extensive benefit from having heat recovery in ventilation systems. Both catalogue data (Exhausto, 2022; Rehva, 2016; Swegon, 2022) and scientific literature confirms this Kragh et al., 2005; De Antonellis et al., 2014, Liu et al., 2010). The efficiency is a matter of an optimization between fan electricity and heat recovery where a larger heat recovery unit gives higher efficiency and higher pressure drop, and apparently in the magnitude of 80% has been found to be a reasonable compromise. We also spend a loyt of time indoors (Lech at al., 1996) which means that the indoor climate as a result of the ventilation is very important.

Heat or energy recovery in ventilation systems have been used extensively and successfully in office buildings for decades but in residential buildings, as mentioned above, this is a rather new phenomenon. Non-residential buildings normally have a higher air change rate and moisture is seldom a problem, as is often the case in dwellings where specific processes like showering and cooking generate a lot of moisture (Nevander and Elmarsson, 2006). This means that non-residential buildings do not have the same problems with frost and there is little experience of the problems that can occur due to freezing. The efficiency of a heat recovery ventilation in frosting conditions have been shown to be remarkably lower and can decrease below 50 % with working frost prevention and even lower without (Nasr et al., 2015; Zhang and Fung, 2015; Justo Alonso et al., 2015; ASHRAE, 2013; Johansson et al., 2023).

Moisture in the ventilation system and in the building is an issue that can both benefit and hit the system's performance and the indoor climate and moisture risks of the building. Heat recovery in mechanical supply and exhaust systems is usually done with a cross-flow counter-flow like plate heat exchanger, or with a rotor. Both types have been used extensively in office buildings for decades, but in homes, they are a fairly new phenomenon. Compared with office buildings, moisture supply is lower and airflow per floor area is considerably higher than in homes where activities like showering and cooking create a lot of moisture (Nevander and Elmarsson, 1994).

Typical problems with mechanical supply and exhaust air handling units are that the temperature efficiency is not the one promised by the manufacturer. Measurements and physical theory can describe the temperature efficiency, but phenomena that occur in reality are often neglected or they are too simplified. An example of this is that the conditions have changed from the test case (ie a non-representative test case), or condensation occur in the exhaust part of the heat exchanger, which has to be simulated with moisture and temperature loads of the building, which vary with the time and residents and this is not done in practice and therefore no optimisation has been made (Bagge, 2011). In terms of temperature efficiency, rotors have higher efficiency than plate heat exchanger at the same volume of the unit. This is especially true in situations where freezing occurs. They are easy to adjust but consist of more technology and moving parts. Another major problem is moisture recovery. Moisture recovery leads to higher relative humidity in winter, which is a solution to the problem of dry air sometimes experienced during the winter, and risk of moisture safety being compromised and the risk of mould growth that is definitely dangerous for the health and well-being of the residents.

Moisture recovery can be handled with increased airflow, which in turn increases the energy use for both heating and electricity. Moisture recovery as a solution to dry indoor environment has not been thoroughly analysed with regard to the building physic design requirements and moisture safety. There is a need to develop a method that manages moisture safety in combination with moisture recovery, necessary airflow and desired relative humidity indoors. Along with the previous point that rotors have a higher temperature efficiency, an optimization must be made of the choice of heat exchanger to achieve the lowest energy use, the best economy and the lowest environmental impact.

Unwanted temperature efficiency can lead to excessive indoor temperatures. This can be partially solved by varying the angular velocity of the rotor or by passing the air past the heat exchanger. Impact of the choice of non-adjustable or adjustable temperature efficiency needs to be analysed.

The conclusions of the problems raised by mechanical supply and exhaust systems are that there is no type that is obviously better than anyone in all situations and in all times. Extensive analysis is required to address the complex problem of installing appropriate and optimized mechanical supply and exhaust systems in new or refurbished houses. For example, the amount of moisture damage can increase rapidly if the problem of moisture recovery is not corrected due to the rapidly increasing amount of residential supply and exhaust air ventilation units, some of them with rotary exchangers.

There is lack of practical knowledge of how to simulate the system with users, building and ventilation systems regarding heat recovery systems, humidity levels and energy use. There is no possibility for the consultant, the owner or the homes to judge the systems, their advantages and shortcomings. There is not even an opportunity to use them properly during the life of the building. Scientifically, there is a lack of models, performed simulations and evaluations of buildings in use to perform optimization regarding moisture safety, energy use, power usage and indoor environment based on the choice of mechanical supply and exhaust systems and their design.

1.1 Aim

This project has solved most of these issues in the comprehensive problem description above. This project optimizes mechanical supply and exhaust systems in homes regarding moisture levels, energy use, power requirements and indoor environment based on which heat recovery system is chosen as well as optimizes parameters for each type of heat recovery system. The project has covered both new construction and existing buildings. The project has collaborated with industry to increase communication and dissemination of the results.

The following parameters and input data are included and discussed.

- Type of heat exchanger
- Relative humidity in the indoor environment, including the possible positive effects of moisture recovery - this is paramount to avoid moisture damage and is due to moisture recovery, airflow and moisture production.
- The need for ventilation airflow - affects the handling of moisture and energy use.
- Heating and electricity use in the building as well as power demand for heating, all of which are important for achieving sustainability goals in society, affecting life cycle economics and environmental impact and thereby the total sustainability.
- User parameters - moisture load, household electricity use, attendance and indoor temperature are resolved over time as they vary and statistical distribution of different homes will be analysed regarding moisture variations.
- Moisture supply measurements in dwellings in Sweden
- Outdoor climate - in cold climate, energy use and moisture recovery increase, hence the interest in cold climate.
- Pressure balance indoors due to the difference between airflow out and in.
- Decentralized air handling units in apartments or single family houses and centralized air treatment units in multi-family houses.
- Variable or constant airflow as a method of reducing energy use.

The result of the project will be comprehensive knowledge as well as tools and guidelines:

- A model describing a residential building as a system that includes heat recovery and occupants - part of the model describes how different component parameters are handled, e.g. an appropriate definition of heat recovery efficiency.
- A simplified tool in that can be used and adjusted by Industry to do simulations that take into account the analysed parameters.
- An analysis of common optimal solutions through simulations with the model and tools.
- An analysis of the development potential of system components for a future with even lower energy use and better indoor environment.

2. Methods

The main core of analysing supply and exhaust ventilation with heat recovery is to make simulations on the physics behind the heat recovery and the moisture of the building. The analysis of realistic cases, scenarios and designs make a need for a number of simplifications and input data. Therefore, measured moisture production behaviour was collected, analysed and taken into consideration in the exemplification of the tool for simulations. Dwellings have been in focus since that is where we have rather high moisture loads. During the project, problems and ideas have been discussed with other researchers as well as with the companies in the business of heat recovery in ventilation systems. At the start of the project, focus was on not getting too high moisture supply and relative humidity in the dwellings by choosing the best performing type of heat recovery. Later in the project, the Covid pandemic hit, and too low relative humidity entered the problem arena. Therefore, some analysis of how moisture can be preserved instead of get rid of was introduced.

To summarize, the result is based on a simplified specific model with the aim to distinguish between typical heat recovery systems for ventilation systems used in Sweden that don't recover moisture and those who does recover moisture. If there is a moisture recovery, the airflow must be increased to end up with the same moisture supply in the dwelling. Moisture recovery is in normal Swedish systems connected to rotary wheels, that tend to have slightly higher temperature efficiency, but also are less prone to frosting, but on the other side, they tend to recover moisture which yields for a slightly higher airflow. On the third hand, that will lower the amount of very low relative humidity hours in winter as well.

2.1 Calculation model

To make the tool for the calculations useful and adjustable and possible to develop for anybody, Excel was this time selected for the programming. A PC program could have been used but is not that changeable. The model must include the connection to the building and its occupants and their moisture production as well as heat dissipation. Dwellings are in focus, and data from 602 dwelling years of moisture supplies are a basis for the exemplification of scenarios. In Swedish dwellings there exists almost no cooling systems. Therefore, this work focuses on the heating energy and the heating scenarios and it is also during the heating seasons there is the main problems with moisture risks and too high moisture supply.

More details of the model will be presented in the paper that are ongoing. Here, an overview is given. A power balance of a dwelling was set up and also a moisture balance based on vapour content expressed in g/m³. The occupant moisture production is expressed in g/h and can be calculated in practice from the 602 measured dwellings years of moisture supply. Moisture supply is defined as the moisture content difference between indoor and outdoor. The moisture supply is the driving factor for moisture transportation through materials, like an external wall, and typical limits of this moisture supply is given to 3 g/m³ (Folkhälsomyndigheten, 2014) or 4 g/m³ (Nevander and Elmarsson, 1994; Arfvidsson et al. 2017). Ventilation in the context of this project is focused on the need for removing away the moisture even if there of course are another reason to ventilate, like getting rid of other emissions. Generally, in Sweden, in dwellings, ventilation is designed for 0.35 l/(s·m²) where the area refers to the floor area.

Flow balance is assumed between supply and exhaust. Usually, a slight under pressure is wanted to avoid moisture convection through the walls, but it is shown (Johansson, 2005) that that does not influence energy use for heating more than very little.

Heat recovery is assumed to be linear to the temperature difference where the temperature out of the heat recovery unit $t_{hr} = (t_{ext} - t_{out})\cdot$temperature efficiency $+ t_{out}$. The temperature efficiency will depend on the airflow and on the condensation if condensation occurs in the extract-exhaust air stream.

The power balance assumed no condensation in the room itself and takes into account heat loads, solar gains from North, East, South and West respectively and leakage based on Johansson (2005) where a certain ratio of the leakage at measurement pressure of 50 Pa with a Blower door is assumed to occur at normal conditions. Ventilation is taken into consideration with a supply temperature that can be either set with a reduction in heat recovery or continue to increase when the temperature from the heat recovery increases. Typically, in a Swedish ventilation system, the temperature efficiency a plate heat exchanger cannot be controlled but for a rotor it can by varying the rotation speed of the rotor. The plate exchanger can be controlled with bypass but this is not commonly done in dwellings.

Here, heat gains from household electricity and people is assumed to be constant while moisture production, as of mass of water added as vapour to the air is varying or constant depending on scenario tested.

Outdoor climate data was taken from normal years form the latest period from Meteonorm (Meteotest, 2019; Johansson, 2008), and the solar gain was simplified to the Meteonorm output of global radiation towards a surface with a specific inclination, vertical, and a direction. Also, temperatures and relative humidities were taken. Mathematical models were used to describe saturation vapour content (Johansson, 2010) and with the relative humidity, the actual vapour content can be described.

The moisture added to the indoor air is assumed to give a certain moisture content indoors, same is in the extract air. This can be handled as a constant, as a regression function connected to the measured data or as “raw” measured data for each year, where 602 different dwelling years exist, of which some dwellings have measurements for more than one year, so number of measured dwellings is lower than 602,

A heat exchanger model based on counter flow was made as a numerical simulation programmed in a macro in VBA in Excel. The aim was to utilize this model for making simplified mathematical models of how temperature can be adjusted for condensation in the extract-exhaust air stream and a lower or higher airflow. The condensation is found to be able to compensate by finding a certain value of vapour content in the indoor air or extract air by finding when to start to compensate with vcomp=7.52*e^(0.0464*tout). Then the compensation was described in a plausible way by $1+(v_{ext}-v_{comp})*0.19/(19.4-v_{comp})$, where v_{ext} is the moisture content indoors. If $v_{ext}>19.4$ g/m³, the compensation is 1.19 and if $v_{ext}<v_{comp}$, the compensation is 1. The compensation is multiplied with the nominal temperature efficiency. The temperature efficiency was found to be possible to compensated for the airflow by $=1/(0.997+0.235*(q/q_{nom})^{1.02})$ where q is the actual flow and $q_{nom} = 0.004736*((1000 - 997*h_{nom})/h_{nom})^{0.9804}$ where hnom is the nominal temperature efficiency at the nominal flow.

Moisture recovery is assumed to work linearly based on practical experience from rotary wheel systems, and in particular this is utilized in offices buildings with cooling to avoid drying air. It is then described in the same way between 0 and 100 % as temperature efficiency.

The fan electricity use is commonly expressed by the SFP value, specific fan power, in the unit if kW/(m³/s), same as W/(l/s). Based on numerous runs in an company internal software for energy calculations in ventilation systems, Swegon System Choice, based on loads of lab measurements and piecewise linear regressions of air handling unit electrical power use, a simplified plausible mathematical model was found to be that the actual $SFP_{act} = SFP_{nom}*q^2/q_{nom}$ where q_{nom} is the nominal airflow giving the nominal SFP value, that is usually known from the design. This model assumes that the same air handling unit is varying the flow in the same system. If the system is redesigned, the SFP_{nom} will also be recalculated together with larger duct system etc. The supply fan air heating was supposed to be based on half the fan electric power. Theoretically in a turbulent system, the electric power is proportional to the cube of the airflow, but from practice, we know that that isn’t the case due to linear losses particularly in filters and heat exchangers (Engdahl, 2002; Engdahl and Johansson, 2004).

Frosting is simplified to a given lowest exhaust air temperature, proposed to 0 °C which is reasonable for plate heat exchangers (Johansson et al., 2019; Johansson et al., 2023). Freezing will occur if the air is not controlled to be very dry. Rotary heat exchangers are not that sensitive to freezing, and for rotary heat exchangers there is a limitation found in in practice that a line in the Mollier chart must not cross the RH = 100 % going from indoor conditions to outdoor conditions. A mathematical model of this was made and a plausible description of lowest possible extract or indoor temperature to avoid frosting is =-24.3+0.362*$RH_{indoors}$, se Figure 0. Here it is assumed a relative humidity of 90% outdoors, and this is not very sensitive. An indoor temperature of 20°C was assumed and a nominal temperature efficiency of 0.83, common for commercial rotary wheel systems. It will be safer if it is drier, but it is not common with low relative humidity outdoor if it is very cold.

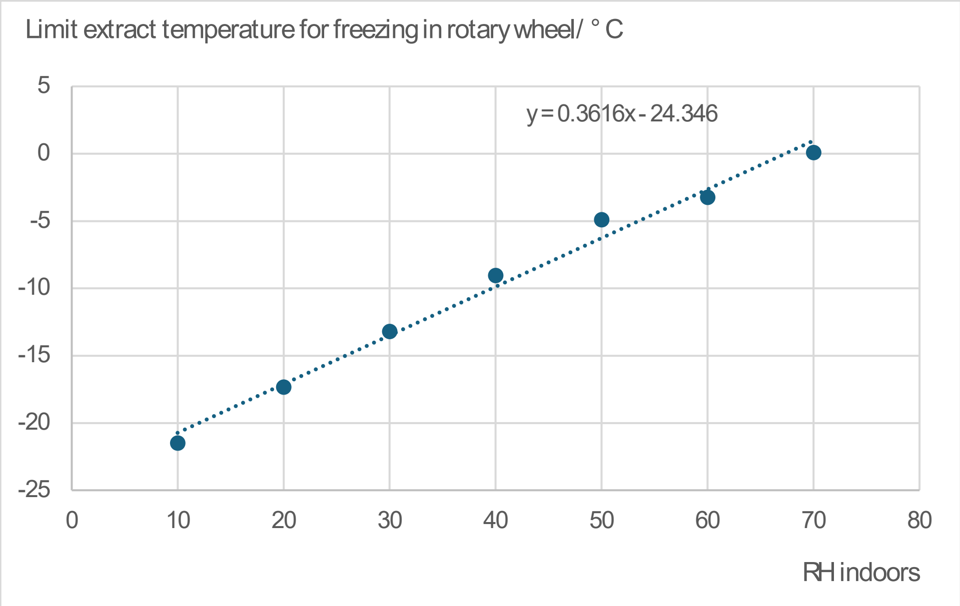

Figure 0. The Limit extract temperatures for a rotary wheel heat exchanger to avoid frosting at 20 °C indoor temperature and 90 % relative humidity outdoors.

The model includes the option to either use a constant or given airflow of the ventilation system or to control it by calculating the flow to give a certain moisture supply based on first hour or for every single hour of the year, alternatively the same thing for a certain relative humidity. In case of moisture supply this can be done explicitly every hour, but in case of relative humidity, iterations are needed, taking much more time to simulate. Typical limit values can be what we find from measurements on average, or 3 g/m³ as recommended in Sweden.

2.2 Default input data

Table 1 shows the included outdoor climates. The presentation is based on results as a function of outdoor temperature. Table 2 shows other default input data to the simulation model with description.

Table 1. Swedish outdoor climates included in the analysis.

Nbr	T_{out_av}/°C	Location
1	8.84	Båstad
2	8.57	Helsingborg
3	8.71	Göteborg
4	8.43	Kalmar
5	8.05	Visby
6	7.84	Stockholm
7	4.24	Skellefteå
8	4.26	Malung
9	2.45	Storlien
10	-1.13	Nikkaloukta
11	4.09	Östersund

Table 2. Model parameters used and their default values.

Ref	Quantity;Paramate	Default	Unit	Description
1	Uav	0.4	W/(m²·K)	Average U-value of entire envolpe
2	Aenv	300	m²	Area of entire envelope
3	g	0.5		g value of windows, heat transmiattance
4	lf	0.8	l/(s·m²)	leakagae factor of envelope, flow per enevelope area at 50 Pa Blower door pressure
5	lffactor	0.05		ratio of lf occuring on average in real situation
6	Afloor	100	m²	Floor area
7	Outdoor climate			The number of the outdoor climate
8	AwinN	3	m²	Window area to North
9	AwinE	3	m²	Window area to East
10	AwinS	3	m²	Window area to South
11	AwinW	3	m²	Window area to West
12	Persons	4		Nominal number of persons
13	Av occupancy ratio	0.5		Gives actual niumber of persons
14	q	35	l/s	Ariflow if airflow is not controlled
15	eta_nom	0.8		Nominal temperature efficiency
16	P_perperson	100	W/person	Power per person
17	P_hous_el	3	W/m²	Power per floor area
18	t_in	22	°C	Indoor temperature
19	t_sa	20	°C	Nominal supply air temperature
20	cond comp	1		0: Condensation is not compensated for; 1:It is
21	qnom_eta	35	l/s	The nominal airflow for airflow compensation of temperature efficiency
22	mr	0		Linear moisture recovery
23	Airflow control	0		0: Constant; 1: Based on moisture supply; 2: Based on RH
24	v_set	1	g/m³	Set point of v if controlled for
25	qmin	10	l/s	Minimun airflow if airflow is controlled
26	qmax	70	l/s	Maximum airflow if airflow is controlled
27	mp	94	g/(person·h)	Moisture production per person
28	SFP_nom	1.5	kW/(m³/s)	Nominal specific fan power
29	q_nom_SFP	35	l/s	The nominal airflow for fan electricty compensation of SFP
30	eta komp	1		0: flow is not compensated for; 1:It is
31	Frosting	1		0: no; 1: t_ext>t_ext_limit;2: rotary whell model
32	Controlable eta			0: temperature after heat recovery can go above t_sa; 1: eta is limited to not overshoot t_sa
33	t_ext_limit	0		limit t_ext_limit for frosting in setting 1

2.3 Moisture production and supply

Measurements of moisture supply were made in 101 apartments during several years and 150 houses during one year. There are generally 5 minutes values that are averaged to hourly values to match the simulation model. The large random expression variation that can usually be seen in data of this type led to that 602 dwelling years of hourly moisture supply data were profiled. These expressed as an equivalent moisture production for the specific example dwelling based on the default data to end up with the same moisture supply. In total approximately 100 000 annual simulations have been made for the results of this report. These measured buildings are further described in the result section.

3. Results

The example results from using the model is presented here to answer some of the questions on how energy use and indoor climate will depend on the use of heat recovery type and different other parameters. For example, if the airflow was set to not change over time, the fan electricity was the same. And is therefore not graphed. Same if there is no moisture Below is a list of used symbols and quantities in this chapter. All given energies refer to the amount during one year, that means they are all annual.

Label	Symbol	Unit	Description
Air heat	Wair	kWh	Annual added heating for the supply air, not from heat recovery
Room	Wroom	kWh	Annual added heating for the room
All heat	Wr	kWh	Annual added heating for supply air and room together
Air power	Pair	W	Maximum power for added heating of the air

3.1 Energy use and resulting indoor climate for different basic temperature efficiencies

Here in Figures 1-17 the nominal temperature efficiency was varied. An average typical moisture supply of 1.1 g/m³ was used to match measurements in total. Fan electricity was 460 kWh in all cases. The presented relative humidity does not depend on the case since there is no moisture recovery. It is clear that frosting in a plate heat exchanger limits the performance, particularly in colder outdoor climates. Practical plate heat exchangers if not designed for high efficiency may have a nominal temperature efficiency slightly below 80% while a rotary heat exchanger may be slightly above 80 %. They can be constructed to be higher but need more space and get higher pressure drops so this is what the business in Sweden has aimed for during decades. A very low temperature efficiency is not very much prone to frosting and condensation seldom occurs in it. Figure 17 points out that at a certain amount of the time, the relative humidity can be very low indoors, particularly in colder outdoor climates.

3.1.1 Air heating

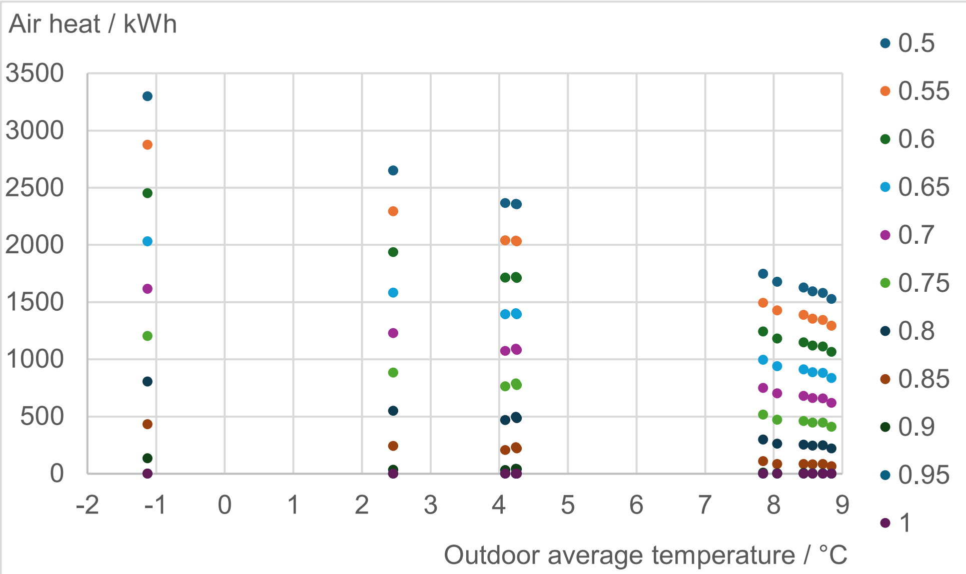

Figure 1. Air heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and it is assumed that freezing does not occur, even if it is not realistic.

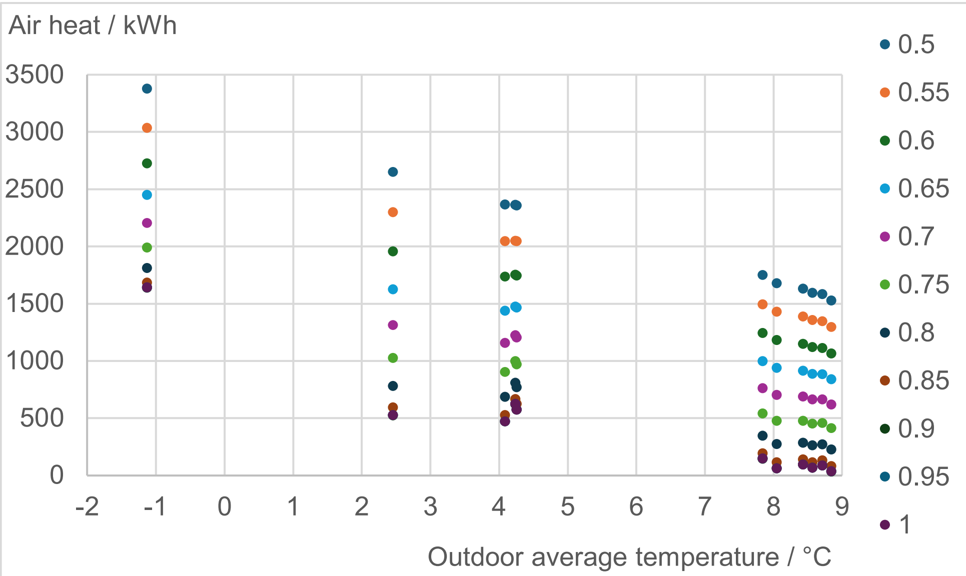

Figure 2. Air heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and no exhaust temperatures below 0°C is assumed as freezing protection.

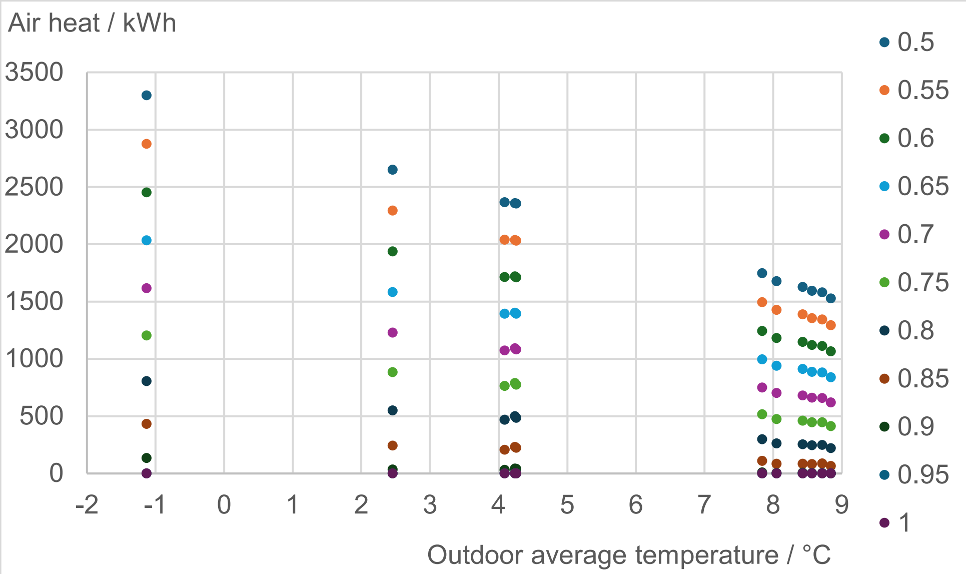

Figure 3. Air heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and it is assumed that freezing does not occur, even if it is not realistic.

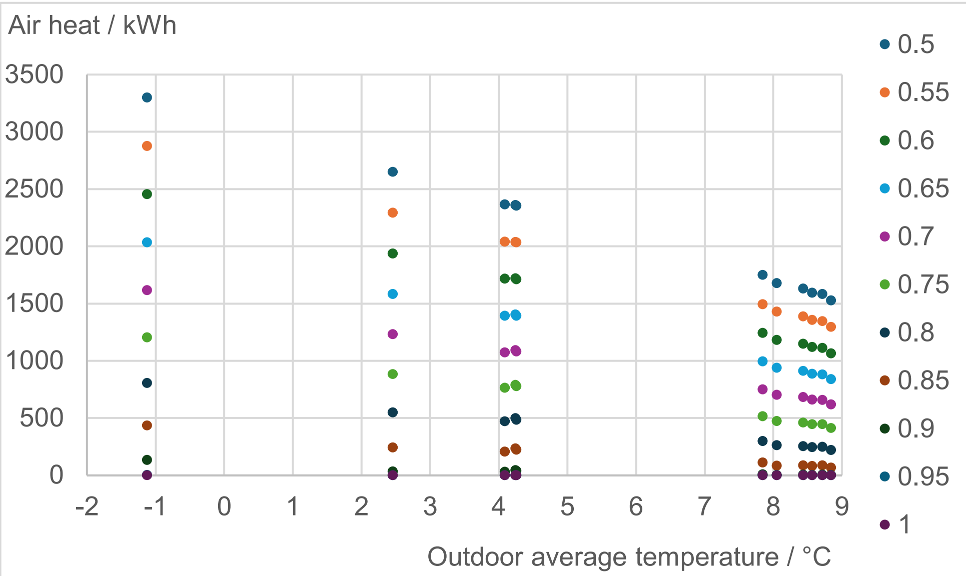

Figure 4. Air heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and the modelled rotary wheel freezing protection is assumed.

3.1.2 Room heating

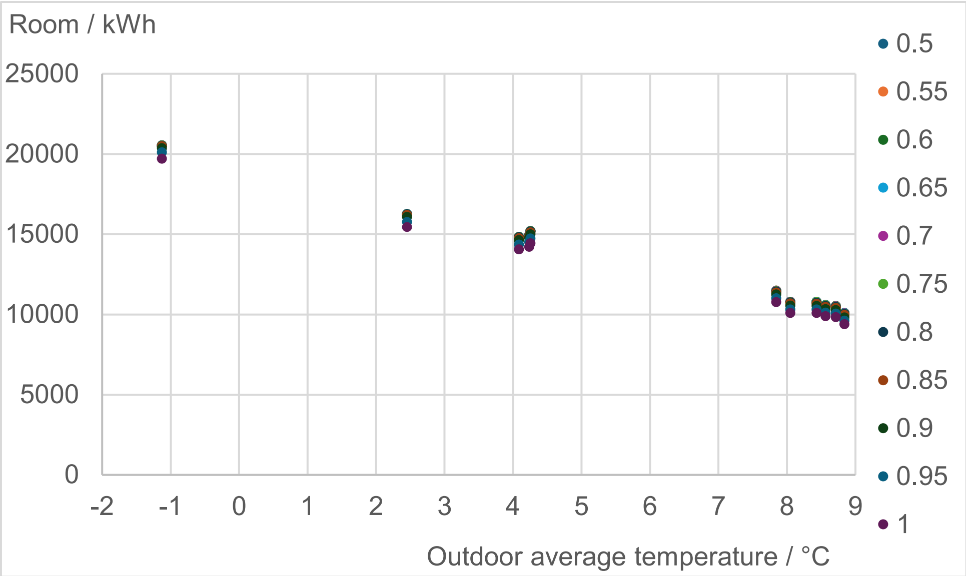

Figure 5. Room heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and it is assumed that freezing does not occur, even if it is not realistic.

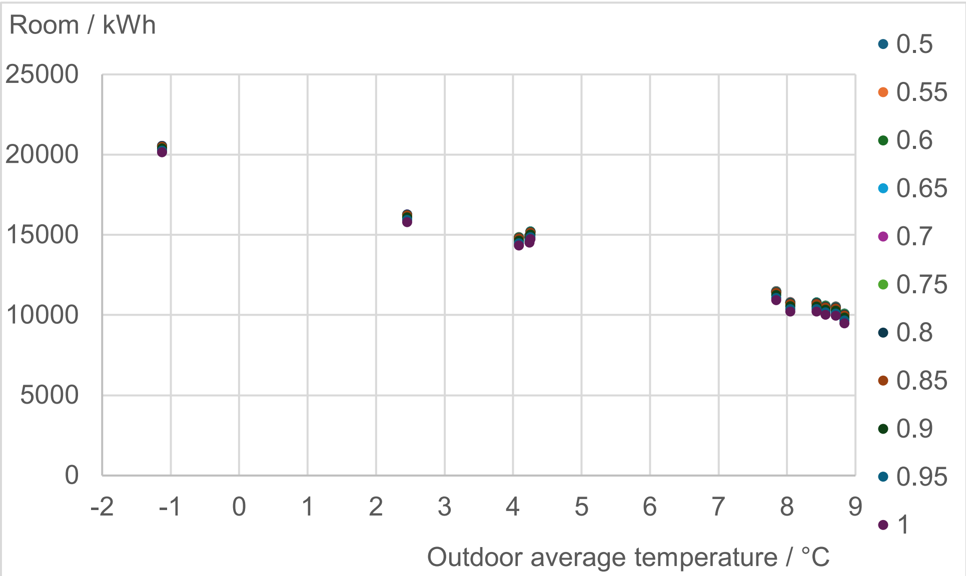

Figure 6. Room heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and no exhaust temperatures below 0°C is assumed as freezing protection.

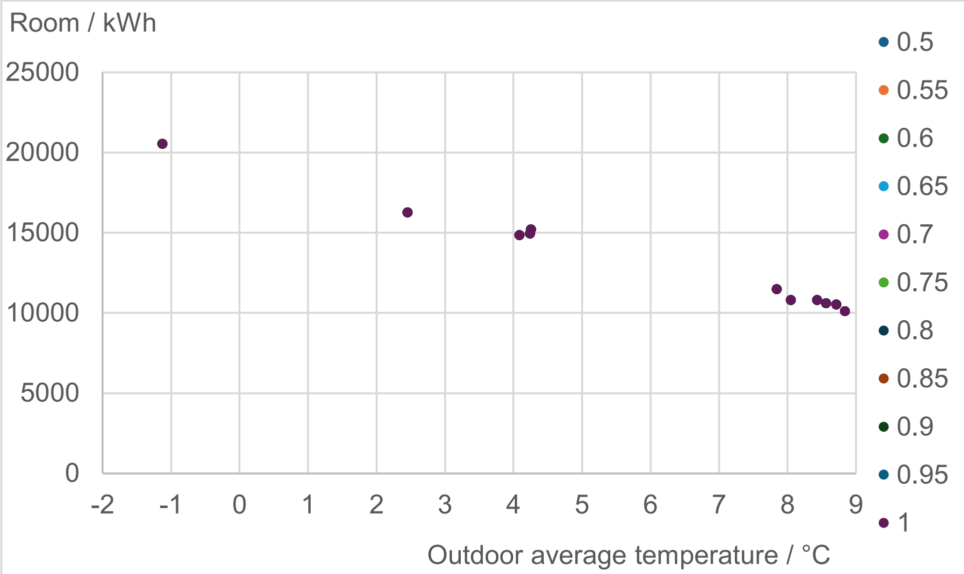

Figure 7. Room heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and it is assumed that freezing does not occur, even if it is not realistic.

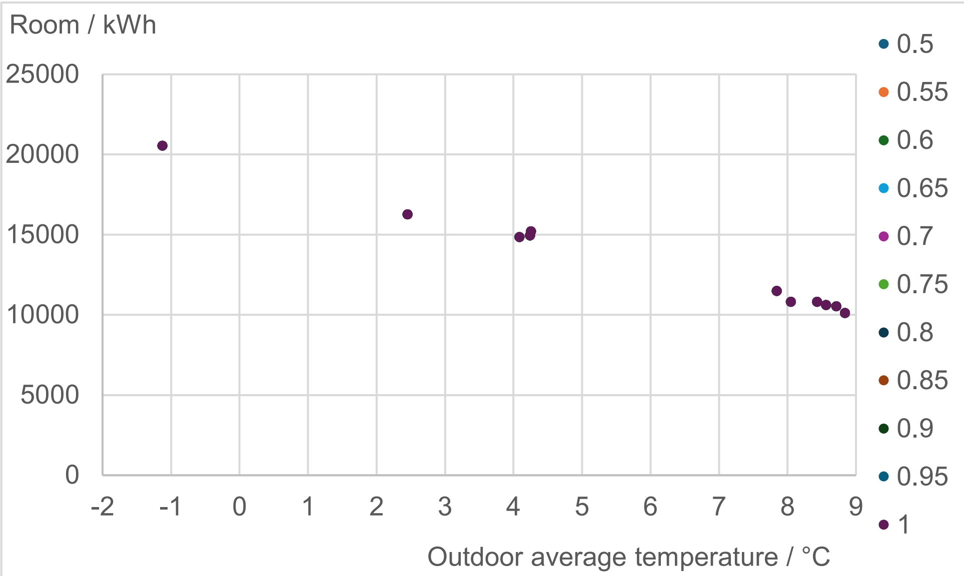

Figure 8. Room heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and the modelled rotary wheel freezing protection is assumed.

3.1.3 Total heating

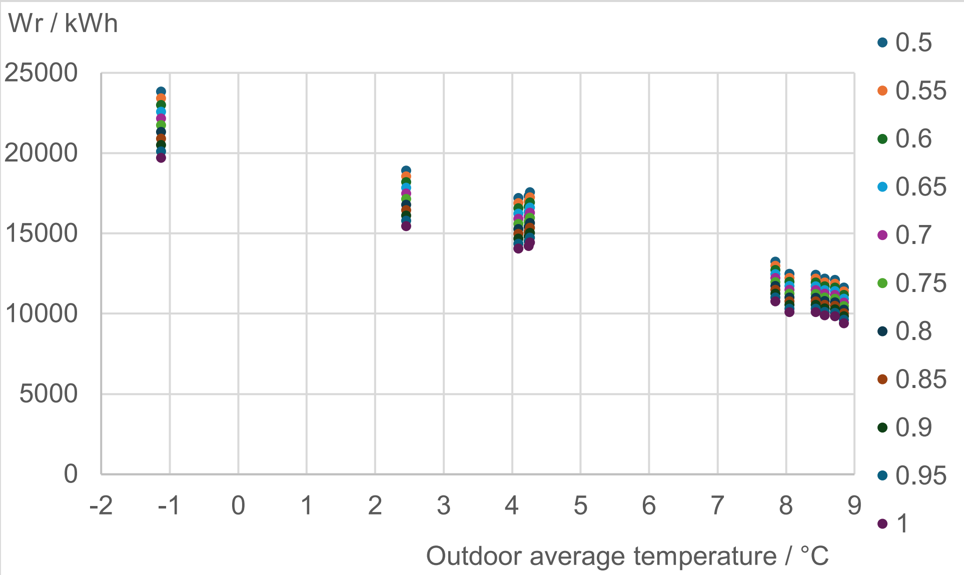

Figure 9. Total heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and it is assumed that freezing does not occur, even if it is not realistic.

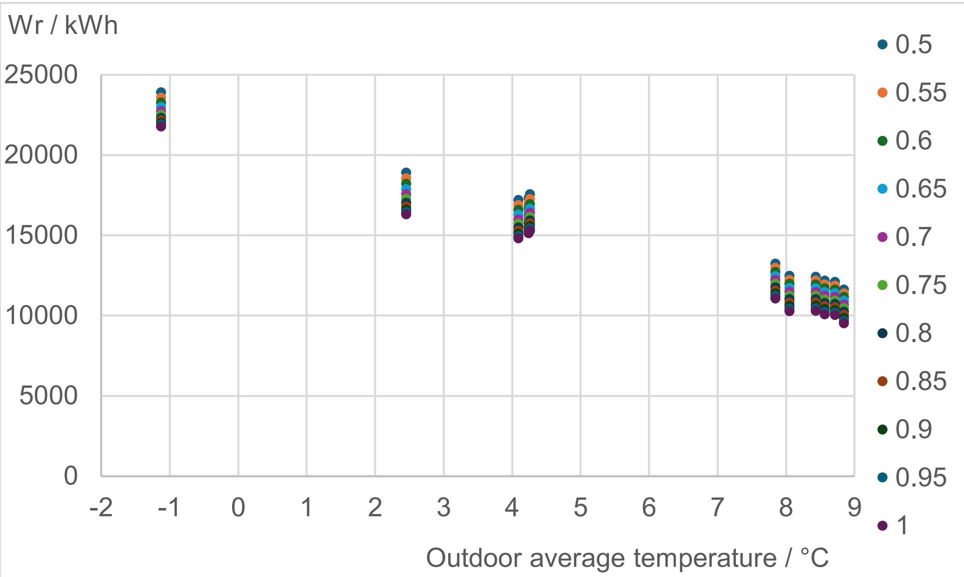

Figure 10. Total heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and no exhaust temperatures below 0°C is assumed as freezing protection.

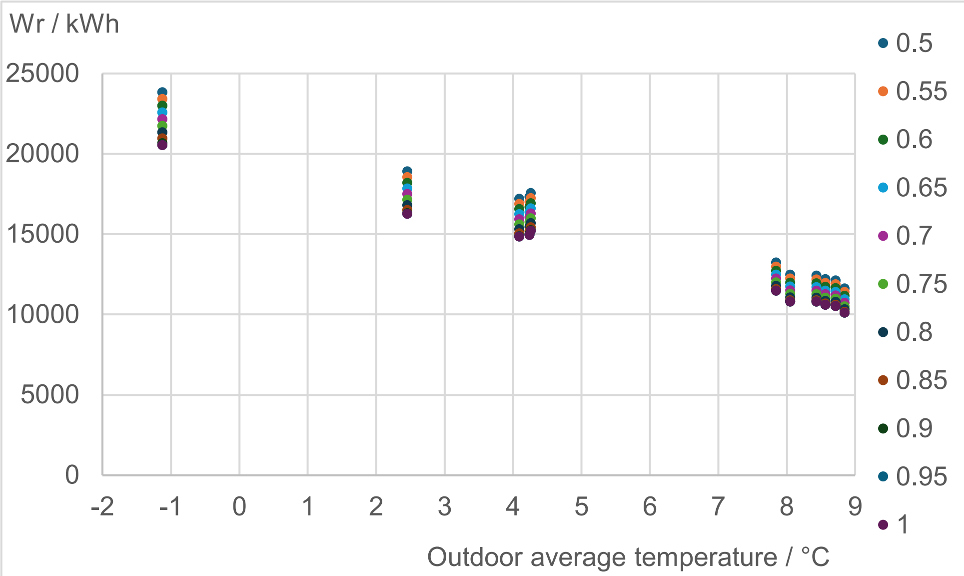

Figure 11. Total heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and it is assumed that freezing does not occur, even if it is not realistic.

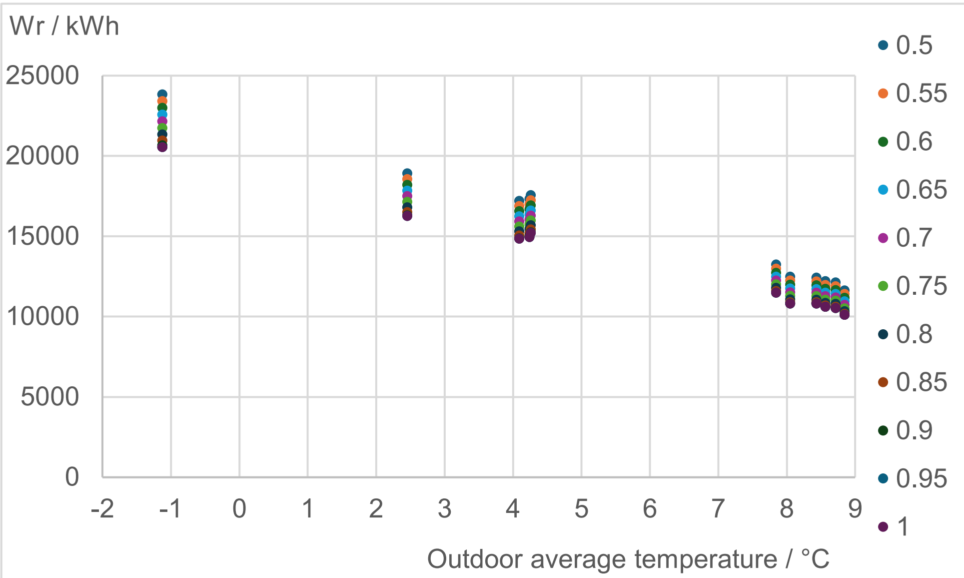

Figure 12. Total heating as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and the modelled rotary wheel freezing protection is assumed.

3.1.4 Max air heating power

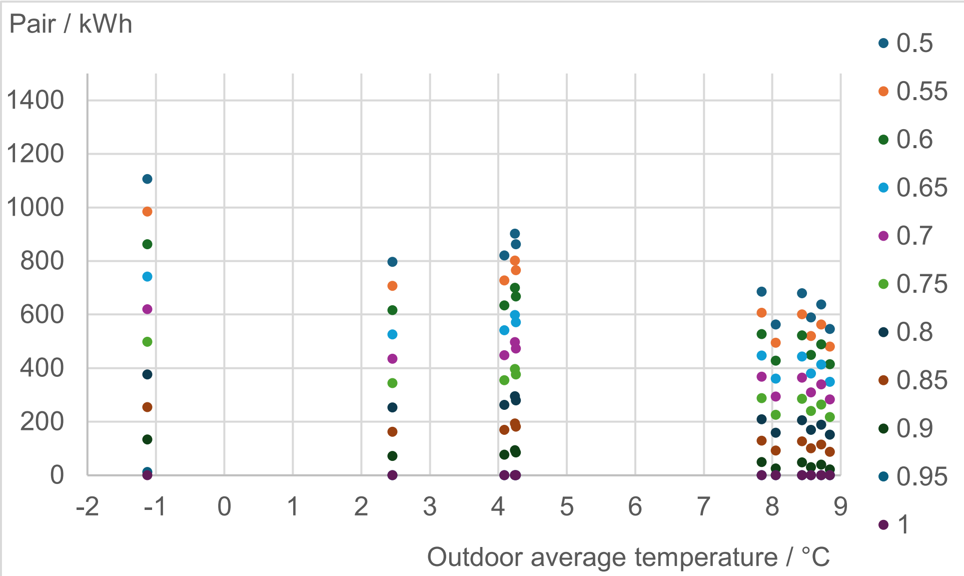

Figure 13. Max air heating power as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and it is assumed that freezing does not occur, even if it is not realistic.

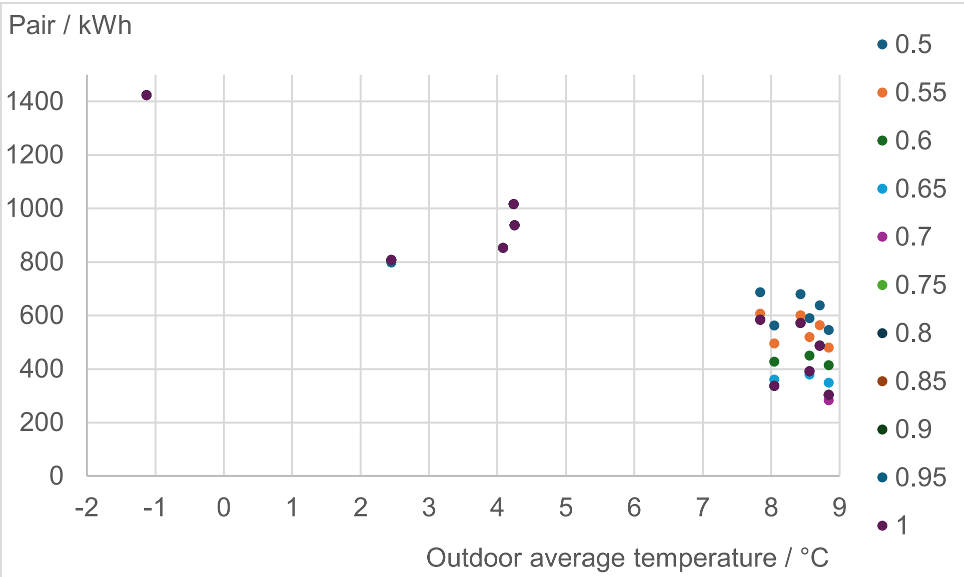

Figure 14. Max air heating power as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. No reset of the temperature efficiency is possible and no exhaust temperatures below 0°C is assumed as freezing protection.

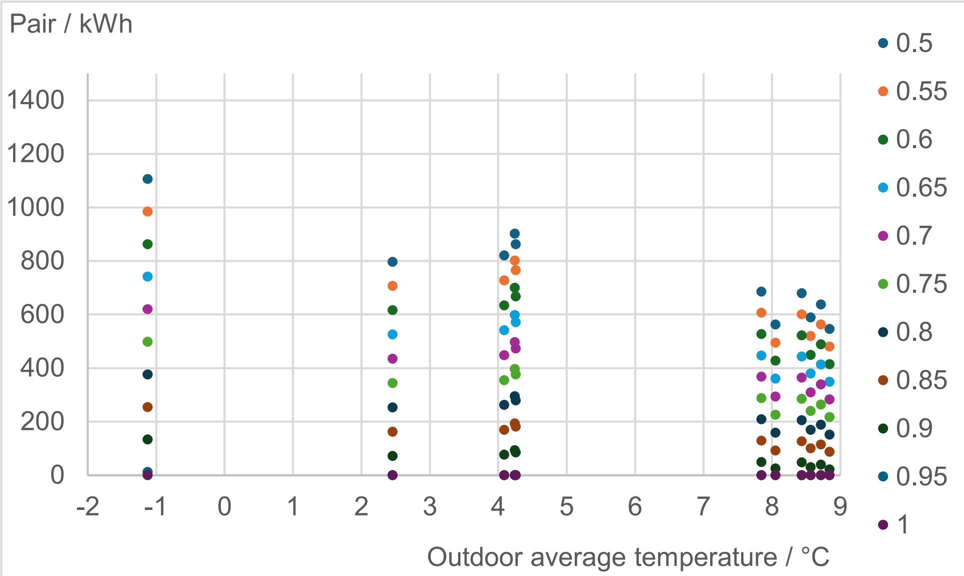

Figure 15. Max air heating power as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and it is assumed that freezing does not occur, even if it is not realistic.

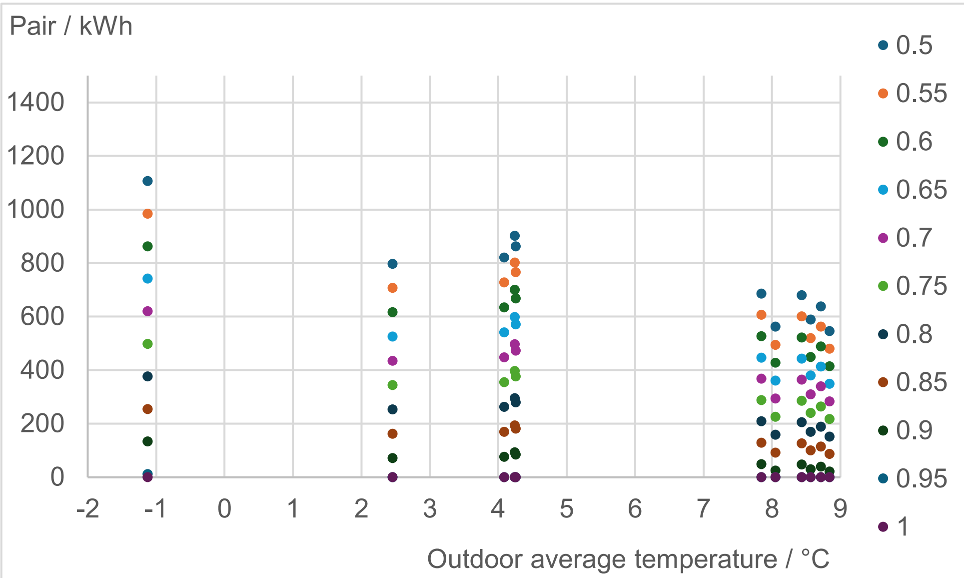

Figure 16. Max air heating power as a function of outdoor average temperature for different nominal temperature efficiencies in the legend. Reset of the temperature efficiency as with rotary wheel is possible and the modelled rotary wheel freezing protection is assumed.

3.1.5 Resulting RH

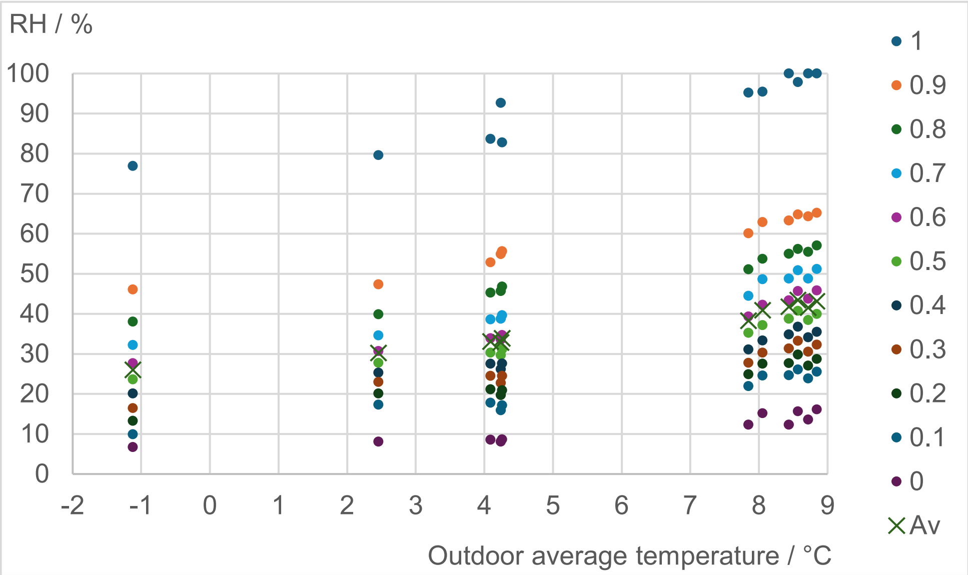

Figure 17. Resulting relative humidity, RH, for all cases as a function of the outdoor average temperature where the legend shows different percentiles of the RH of the indoor climate.

3.2 Moisture supply and moisture production

Moisture supply is defined as the difference between the vapor content of indoor and outdoor air. Moisture enters indoor air from sources such as humans, animals, plants, dishwashing, laundry, bathing, showering, and cooking. The amount of moisture added, the volume of the space, and the ventilation rate determine the indoor vapor pressure. Consequently, occupant behaviour and habits such as the number of residents, showering frequency, and ventilation practices largely influence the magnitude of the moisture supply. Occupant behaviour changes over time; for example, it is commonly noted that showering frequency in bathrooms of 1960s buildings is higher today compared to when they were new (Bagge et al., 2010).

By considering reasonable scenarios in a dwelling, different levels of moisture supply can be estimated. Based on a given amount of moisture added to a volume, combined with a certain ventilation rate over a specified time, the moisture supply can be calculated. For instance, if a family and guests eight people in total gather in a 20 m² living room of a three-room apartment in Stockholm on December 24 to watch an animated film, and the air change rate is 0.5 h^{-1}, a rough calculation indicates that the moisture supply after two hours will be 10.5 g/m³. If the guests stay overnight and all eight people share two bedrooms (four per room), and one bedroom is 10 m² with ventilation designed for two occupants (4 l/s per occupant), the moisture supply after eight hours with four people will be 3.5 g/m³. If the occupants reduce ventilation by half due to perceived drafts, the moisture supply after eight hours will instead be approximately 7 g/m³. These examples provide an estimate of potential moisture supply levels in different rooms under specific scenarios. However, it is not possible to simulate occupant behaviour using simple theory; therefore, understanding actual conditions in dwellings requires measurements in real homes.

3.2.1 Measurements in apartments

Measurements conducted in three buildings located in three Swedish cities have been analysed for use in the simulations of heat recovery in supply and exhaust ventilation systems. The apartments in Building 1 and Building 2 are rental units, whereas the apartments in Building 3 are owner-occupied. The measured buildings were equipped with a ventilation system where the total exhaust airflow from each apartment was accessible in a single duct located in the attic, where the measurement equipment was installed. Although one of the buildings dates back to the 1960s, it has an updated ventilation system. Two of the buildings have mechanical supply and exhaust ventilation, while one building has a mechanical exhaust-only system. Both buildings with mechanical supply and exhaust ventilation feature heat recovery between supply and exhaust air, one using a rotary heat exchanger and the other a plate heat exchanger. Thus, three different ventilation systems are represented among the studied buildings. Two of the buildings contain a mix of apartments with 2, 3, and 4 rooms plus kitchen, while one building exclusively consists of 3 room plus kitchen apartments.

Temperature and relative humidity were measured in the exhaust air duct serving all exhaust air from each apartment. Exhaust terminals were located in the apartments' kitchens, bathrooms, closets, and toilets. For buildings with mechanical supply and exhaust ventilation, outdoor temperature and relative humidity were measured in the outdoor air duct as close to the intake as possible. In the building with mechanical exhaust ventilation, outdoor climate was measured using a weather station placed on the building's roof, on the north side of the air handling unit room. This placement ensures protection from direct solar radiation except during early mornings and late evenings in summer. Since measurements were conducted over several years, a wider variation in outdoor climate is available for studying moisture supply, along with multi-year data.

The temperature and RH sensors used have a specified accuracy of ±1.5% RH for RH between 0 and 80%, and ±2% RH for RH between 80% and 100%. Temperature accuracy is specified as ±0.25°C for temperatures below 0°C and ±0.1°C for temperatures around 20°C. The measurement equipment was delivered calibrated by the manufacturer. When the system was dismantled, the sensors were verified to deviate minimally from the specified accuracies.

Measurements of relative humidity and temperature include potential influences from the building and furnishings' moisture buffering and thermal capacity. If the buildings exhibit air leakage through the envelope, certain outdoor conditions may result in some indoor air bypassing the ventilation unit and thus the central exhaust measurement point. Nevertheless, the measured value represents the exhaust air conditions. Moisture supply determined from exhaust air measurements is representative of the apartment as a zone, although rooms without exhaust terminals may exhibit different moisture levels. The airflow path from supply to exhaust suggests that moisture supply is likely lower in other rooms than at the exhaust terminals. However, poor air mixing could lead to stagnation zones with higher moisture levels, for example, if several occupants sleep with closed bedroom doors. Previous measurements in apartments with supply and exhaust ventilation have shown relatively high air exchange efficiency.

Based on measured temperatures and relative humidities, vapor contents were calculated. The difference between vapor content measured in each apartment's exhaust air and in outdoor air defines the apartment's moisture supply in the unit of g/m³. Measuring in the exhaust air ensures inclusion of moisture from cooking, showering, and laundry, which would not necessarily be captured by a single-point measurement within the apartment. This means that the moisture supply reflects the apartment's total moisture contribution. Measurements were taken every six minutes, and hourly moisture supply was calculated based on the hourly mean of indoor and outdoor temperature and relative humidity. If measurements had been taken at longer intervals, such as hourly, many moisture-generating activities could have been missed. For example, cooking and showering typically last less than one hour.

Figure 18 presents the monthly mean and median moisture supply for the different buildings. As expected, there is significant seasonal variation, with the highest moisture supply during winter and the lowest during summer. Generally, moisture supply decreases month by month from January to July and increases from July to December. Individual apartment profiles show that moisture supply can vary in the opposite direction and exhibit large differences between months. Measurements reported by Boverket (2009) were conducted over 14-day periods during winter and indicate an average moisture supply for multi-family dwellings of 1.2 g/m³, with approximately 3% of apartments exhibiting a moisture supply between 4 g/m³ and 4.99 g/m³. Comparing the mean curves for moisture supply in the studied buildings shows that Building 1 and Building 3 have values roughly consistent with Boverket's (2009) reported average.

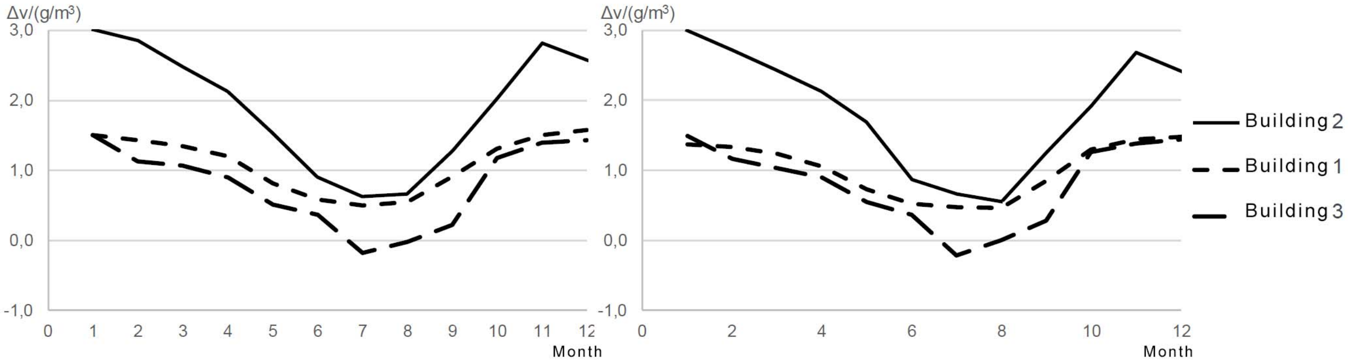

Figure 18. Annual variation of moisture supply in 2015 for the three buildings. Mean value for all apartments in each building shown on the left, and median on the right.

Two linear regression lines were applied in the indoor climate models for mean moisture supply, one for temperatures below 20°C and one for temperatures above 20°C. The levels "Mean" and "95th percentile" are based on values in the chapter Mean Moisture Supply, which describes moisture supply in an average apartment and in a 95th percentile apartment. The intersection of the two regression lines determines which line applies at a given temperature. The "Maximum" level is based on two lines covering all highest measured values, determined by two points within each temperature interval. These points represent the tangents of the lines within each interval. The "Maximum" level describes the highest mean moisture supply during the measurement period for different outdoor temperatures. Figures 19 - 22 present the indoor climate models for each building and for all apartments combined. The figures include all equations describing moisture supply for the different levels and temperature intervals.

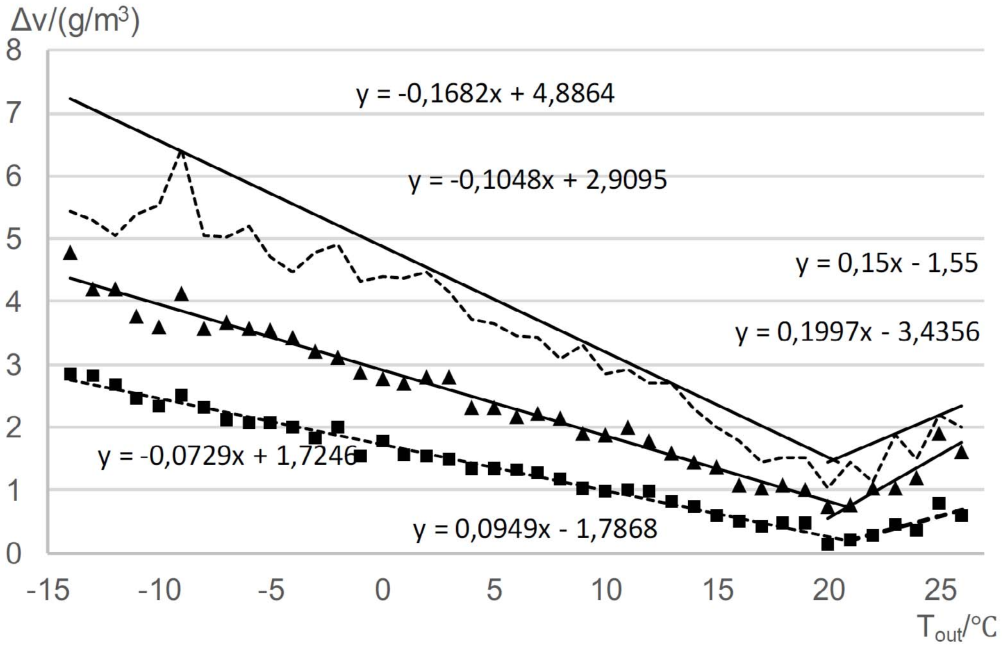

Figure 19. Building 1. Indoor climate model describing the daily mean moisture supply based on measurements in 36 apartments. Moisture supply is presented at the levels average, 95th percentile and maximum. The upper dashed line represents the highest measured moisture supply in any apartment.

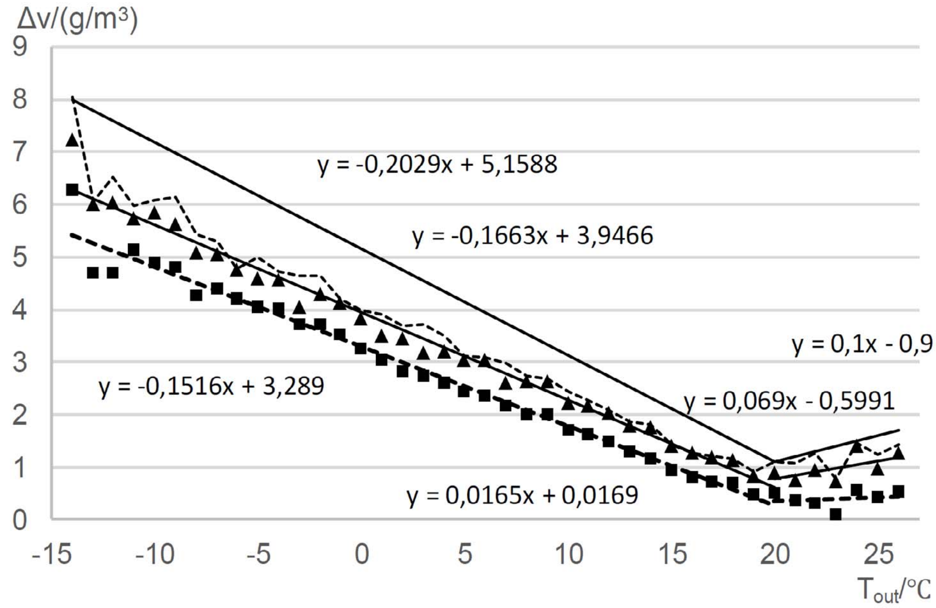

Figure 20. Building 2. Indoor climate model describing the daily mean moisture supply based on measurements in 22 apartments. Moisture supply is presented at the levels average, 95th percentile, and maximum. The upper dashed line represents the highest measured moisture supply in any apartment.

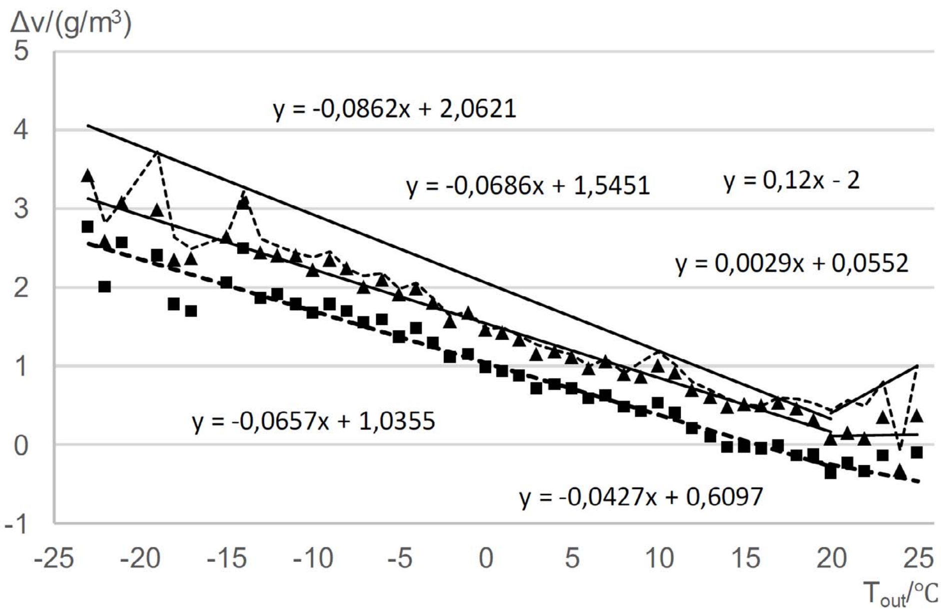

Figure 21. Building 3. Indoor climate model describing the daily mean moisture supply based on measurements in 23 apartments. Moisture supply is presented at the levels average, 95th percentile and maximum. The upper dashed line represents the highest measured moisture supply in any apartment.

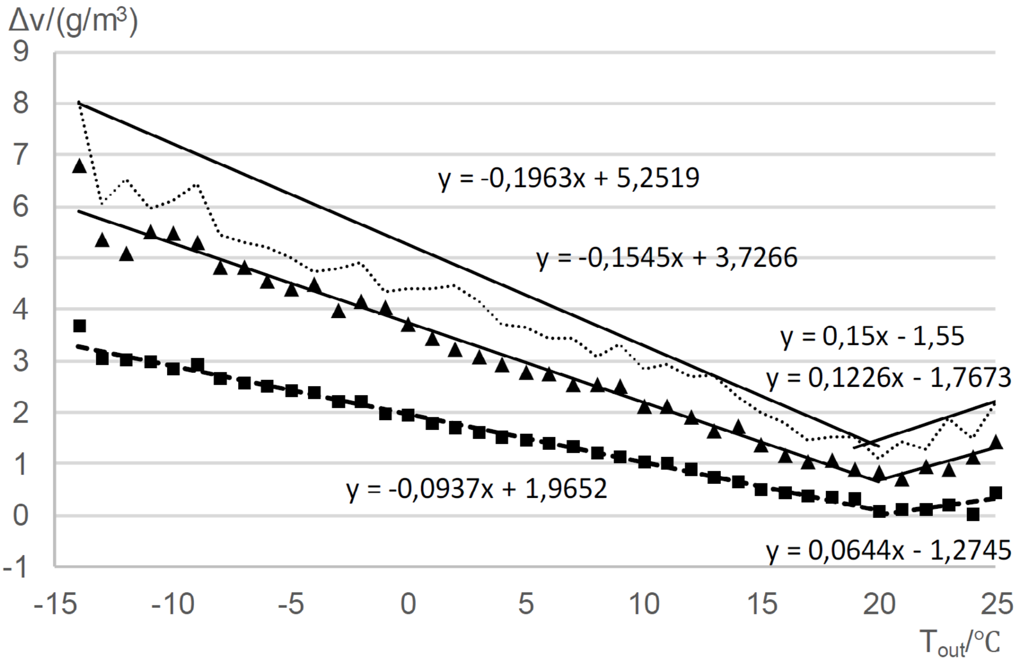

Figure 22. Indoor climate model describing the daily mean moisture supply based on measurements in 81 apartments. Moisture supply is presented at the levels average, 95th percentile and maximum. The upper dashed line represents the highest measured moisture supply in any apartment.

A PC program has been developed to generate data based on these indoor climate models. The program produces hygrothermal parameters derived from the models using user-input outdoor temperatures. The program is freely available at: http://www.hvac.lth.se/resurser/.se. Figure 23 shows the program interface. Users can select which indoor climate model to apply and which level to use for data generation.

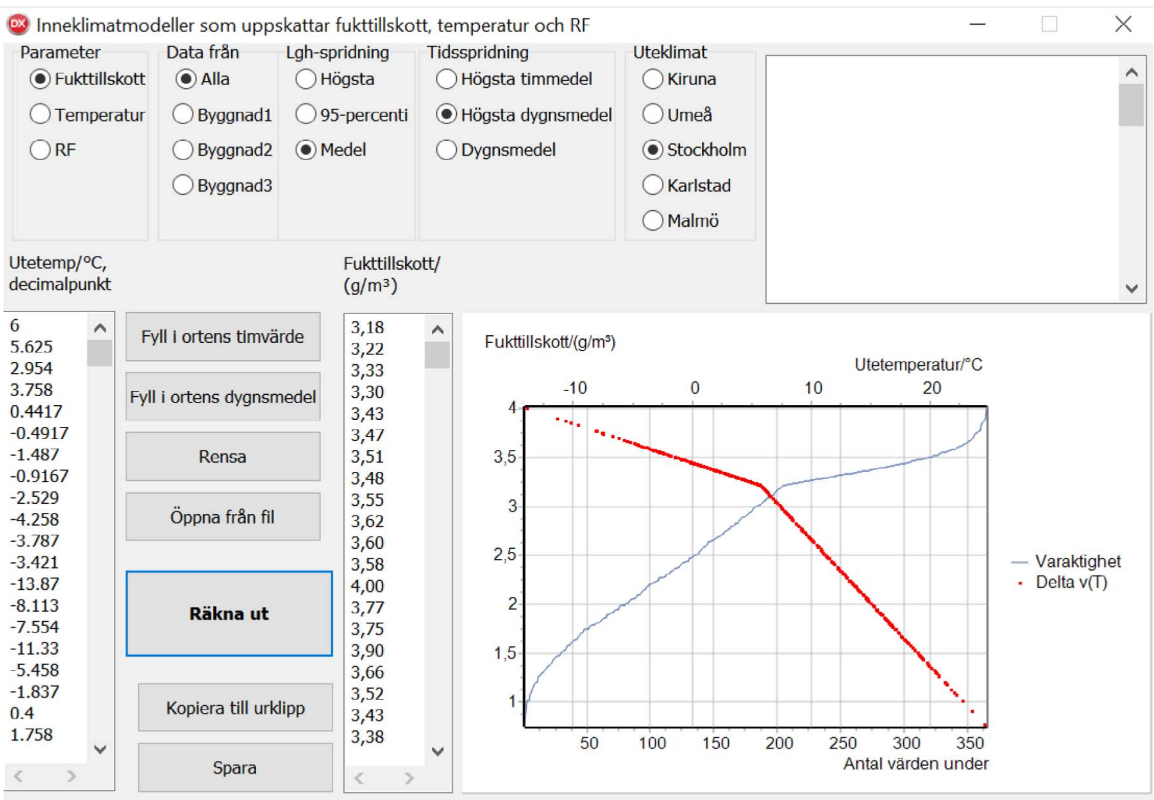

Figure 23. The interface of the PC-program that produce data based on the three buildings' result presented. .

Another 20 apartments were measured in Halmstad with two loggers in each apartment representing the main areas of an apartment. These apartment had mechanical ventilation and in general were suspected to have rather high occupancy. Measurements were taken every 5 minute and averaged to hourly resolution to catch all events but also filter very short variations. Figure 24 shows the duration curves of each of these 20 dwellings. The total average moisture supply was 1.39 g/m³.

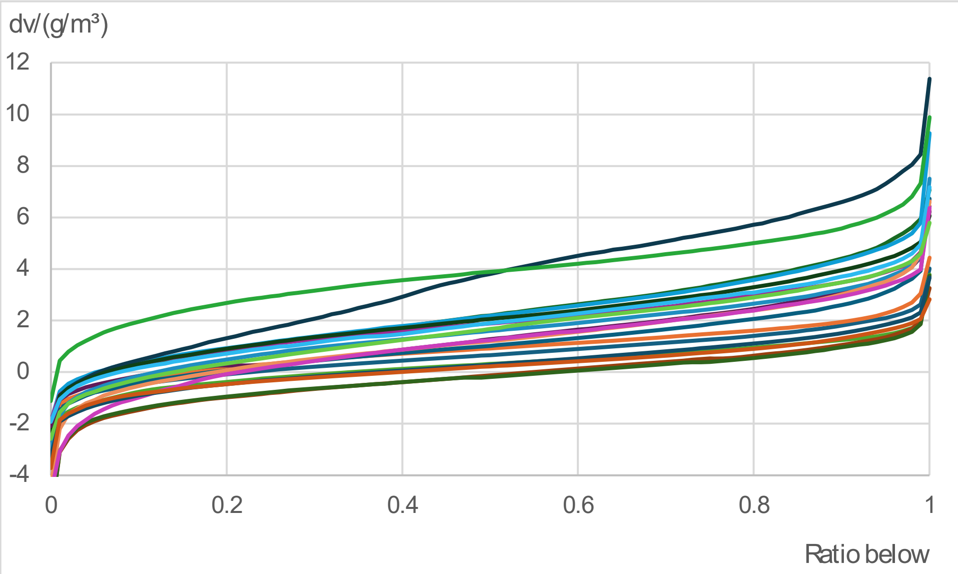

Figure 24. The duration of the moisture supply of the 20 apartments in Halmstad.

3.2.2 Measurements in houses

For houses, 219 annual profiles of moisture supply measurements were analysed and used as part of the simulations of heat recovery in supply and exhaust ventilation systems. In these 150 houses, spread over Sweden in Malmö, Karlskrona, Hässleholm, Visby, Jönköping, Skara, Stockholm, Karlstad, Falun, Sundsvall, Östersund, Umeå, Piteå and Kiruna, loggers were placed in general parts of the living space in the typical self-owned, detached houses built between 2006 and 2015. Measurements were taken every 5 minute and averaged hourly for further analysis.

Based on measured temperatures and relative humidities, vapor contents were calculated. Outdoor vapor contents were determined from measurements at nearby SMHI climate stations or from measurements taken adjacent to the buildings. Hourly moisture supply was calculated for each hour.

Figure 25 presents mean values and selected percentiles for monthly mean moisture supply of the houses across 12 different locations except Jönköping and Umeå. As expected, and consistent with previous studies both in Sweden and internationally, there is significant seasonal variation, with the highest moisture supply during winter and the lowest during summer. Differences in moisture supply between warm and cold periods may be attributed to factors such as extensive window airing during summer, seasonal cooking habits, and drying laundry outdoors in summer but also different driving potential with lower RH indoor in winters. Figures 26 and 27 similarly present percentiles for monthly mean moisture supply measured in houses in Jönköping and Umeå. The results demonstrate relatively large differences in moisture supply between buildings, consistent with findings from other studies.

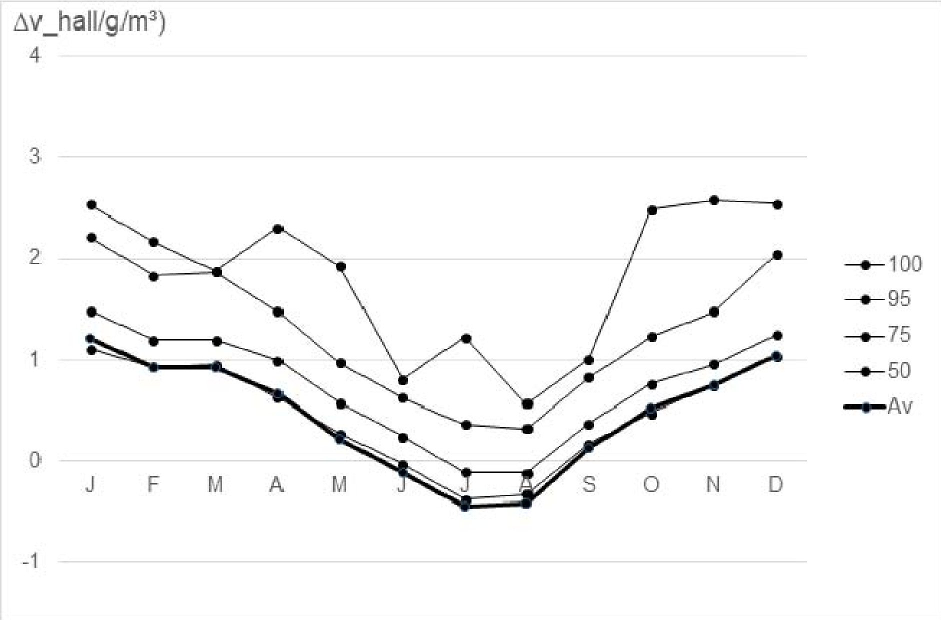

Figure 25. The monthly average values of the moisture supply in the 50 houses in Malmö, Karlskrona, Hässleholm, Visby, Skara, Stockholm, Karlstad, Falun, Sundsvall, Östersund, Piteå and Kiruna for the different percentiles in the legend.

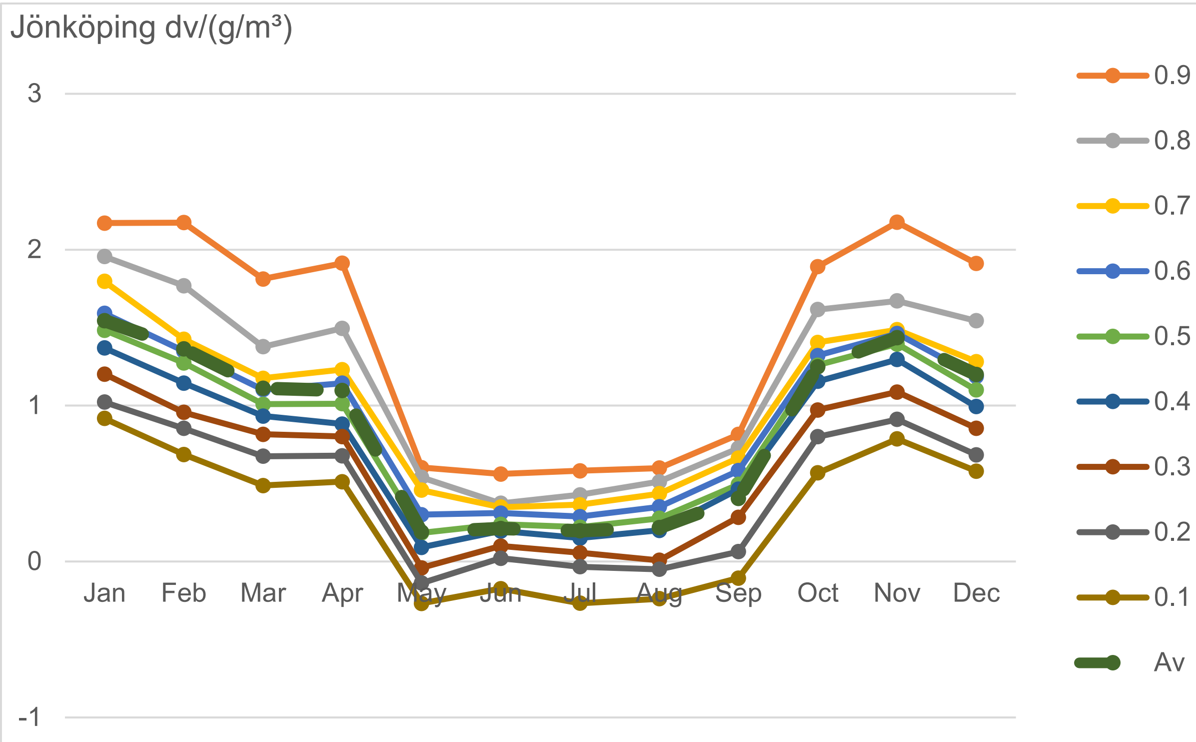

Figure 26. The monthly average values of the moisture supply in the 50 houses in Jönköping for the different percentiles in the legend.

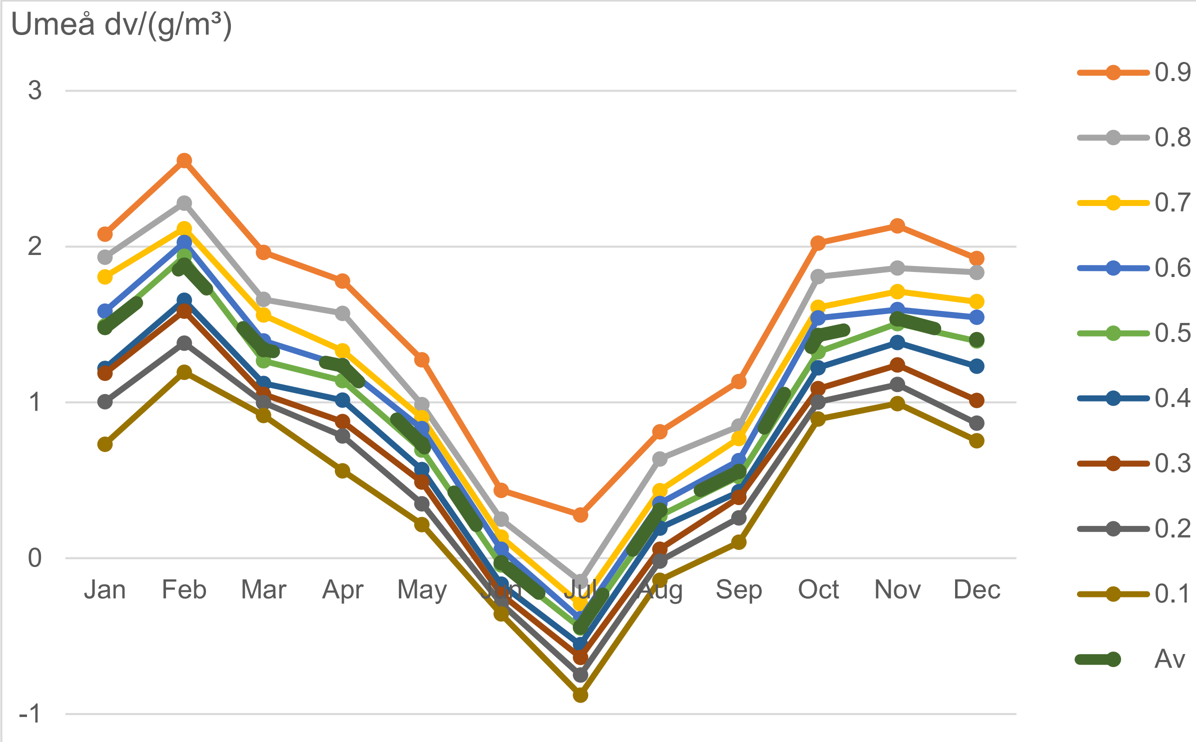

Figure 27. The monthly average values of the moisture supply in the 50 houses in Umeå for the different percentiles in the legend.

Figures 28 and 29 present moisture supply in houses across 12 locations except Jönköping and Umeå as a function of outdoor temperature. Daily mean moisture supply for each house was sorted by daily mean outdoor temperature in steps of whole degrees with an interval of ±0.5°C. For each house and each outdoor temperature interval, the mean moisture supply was calculated. Thus, the figures show mean values and percentiles for daily mean moisture supply (primary y-axis) during days with a given outdoor temperature (x-axis). The secondary y-axis shows the proportion of houses with data for the specified daily mean temperature. Due to climate differences between northern and southern Sweden and the distribution of houses across the country, data for extreme high and low temperatures are available only for a smaller proportion of houses. Here it is split on the overall hallway and also the bedroom separately.

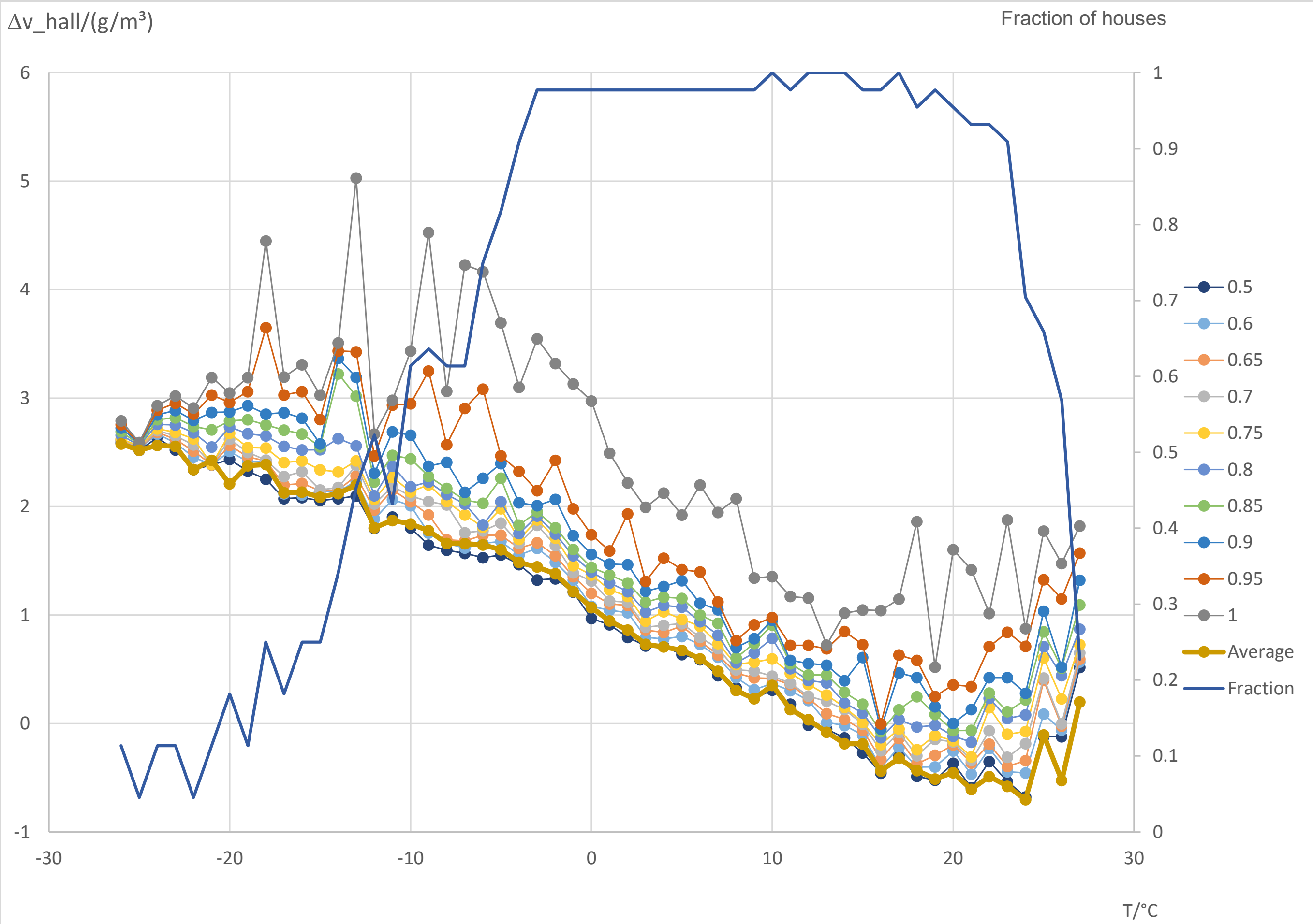

Figure 28. Moisture supply in hallways as a function of outdoor temperature, daily mean values, based on measurements in houses in Malmö, Karlskrona, Hässleholm, Visby, Skara, Stockholm, Karlstad, Falun, Sundsvall, Östersund, Piteå and Kiruna. The secondary y-axis shows the proportion of houses on which the percentiles at a given outdoor temperature are based.

Supply and exhaust ventilation with heat and moisture recovery

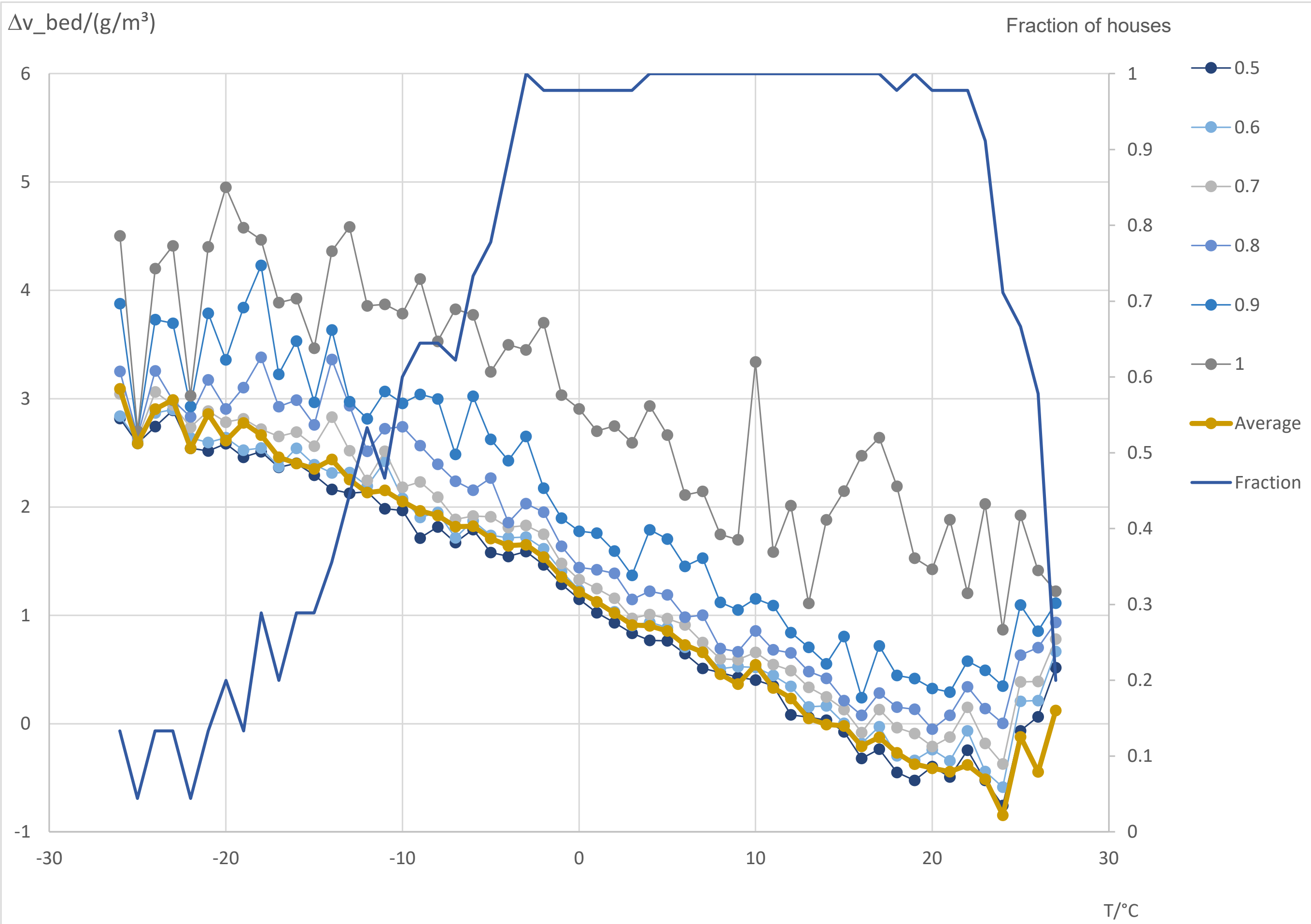

Figure 29. Moisture supply in bedrooms as a function of outdoor temperature, daily mean values, based on measurements in houses in Malmö, Karlskrona, Hässleholm, Visby, Skara, Stockholm, Karlstad, Falun, Sundsvall, Östersund, Piteå and Kiruna. The secondary y-axis shows the proportion of houses on which the percentiles at a given outdoor temperature are based.

3.3 The low RH issue

During this project, the problems related to infectious spread and low relative humidity during the Covid pandemic opened for a track looking at how too low relative humidities could be increased by help of the ventilation system and how severe the problem might be related to dwellings. Three sub studies were made on this subject, summarized below. Generally, there is a disadvantage with very low relative humidities and we also now that very high relative humidities risk problems. There is also clearly measured low relative humidities in dwellings measured and reported. The first report goes through the literature to find how health may be related to indoor relative humidity. The second report measures and analyses the relative humidity and its influence on occupants in elderly homes. The third report evaluates green walls and moisture recovery in rotary wheels as a measure to increase the low relative humidity in offices during winter. Here offices were in subject because rotary wheels are much more common, there, and test are much easier to perform than in occupied dwellings.

3.3.1 Indoor Relative Humidity Levels and Perceived Symptoms in Elderly Homes in Sweden During Winter Season

This study (Ruano Espinoza and Nazir, 2022) investigated indoor relative humidity (RH) levels and perceived symptoms in elderly homes across Sweden during winter months. The research focuses on three locations Luleå (North), Norrköping (Central), and Göteborg (South) and examines correlations between RH, vapour content, and health-related symptoms among residents and staff. Measurements of

RH, temperature, and CO_2 were combined with questionnaire responses to assess indoor climate conditions and their potential health impacts.

People spend approximately 90% of their time indoors, with elderly individuals spending even more time indoors due to reduced mobility. Dry indoor air, particularly RH below 30%, is associated with symptoms such as irritated eyes, dry throat, and skin problems. Conversely, high RH (>60%) can lead to mould and mite growth. Swedish building regulations lack minimum RH guidelines, making this parameter critical for study.

The study employed a mixed-method approach: Literature review on RH and health effects, Physical measurements of RH, temperature, and CO_2 in three elderly homes using sensor data from the building owner, and last, weekly questionnaires to staff regarding perceived symptoms. Correlation analysis between measured data and reported symptoms were made and also comparative analysis across locations. Data were collected from December to mid-April.

Key results were:

- Luleå exhibited the driest conditions: 78% of time below 20% RH with an average RH of 23%.
- Norrköping had average RH = 32% and Göteborg 35%.
- CO_2 levels were consistently below 1000 ppm, indicating adequate ventilation.
- Questionnaire responses revealed common symptoms: dry throat, irritated eyes, and dry/red skin. Severity was generally mild, though some cases in Göteborg reached moderate levels.
- No strong correlation between RH and symptom prevalence due to narrow RH range and limited responses.

The findings confirm that elderly homes in northern Sweden experience significantly lower RH during winter, exposing residents to conditions associated with discomfort and potential health risks. While symptoms were reported, the study could not establish definitive correlations due to methodological limitations, including low response rates and absence of medical examinations. Future research could include longer measurement periods, summer data, and medical assessments to strengthen conclusions. Maintaining RH between 35 and 50% is recommended to reduce health risks. Figures 30-32 shows results.

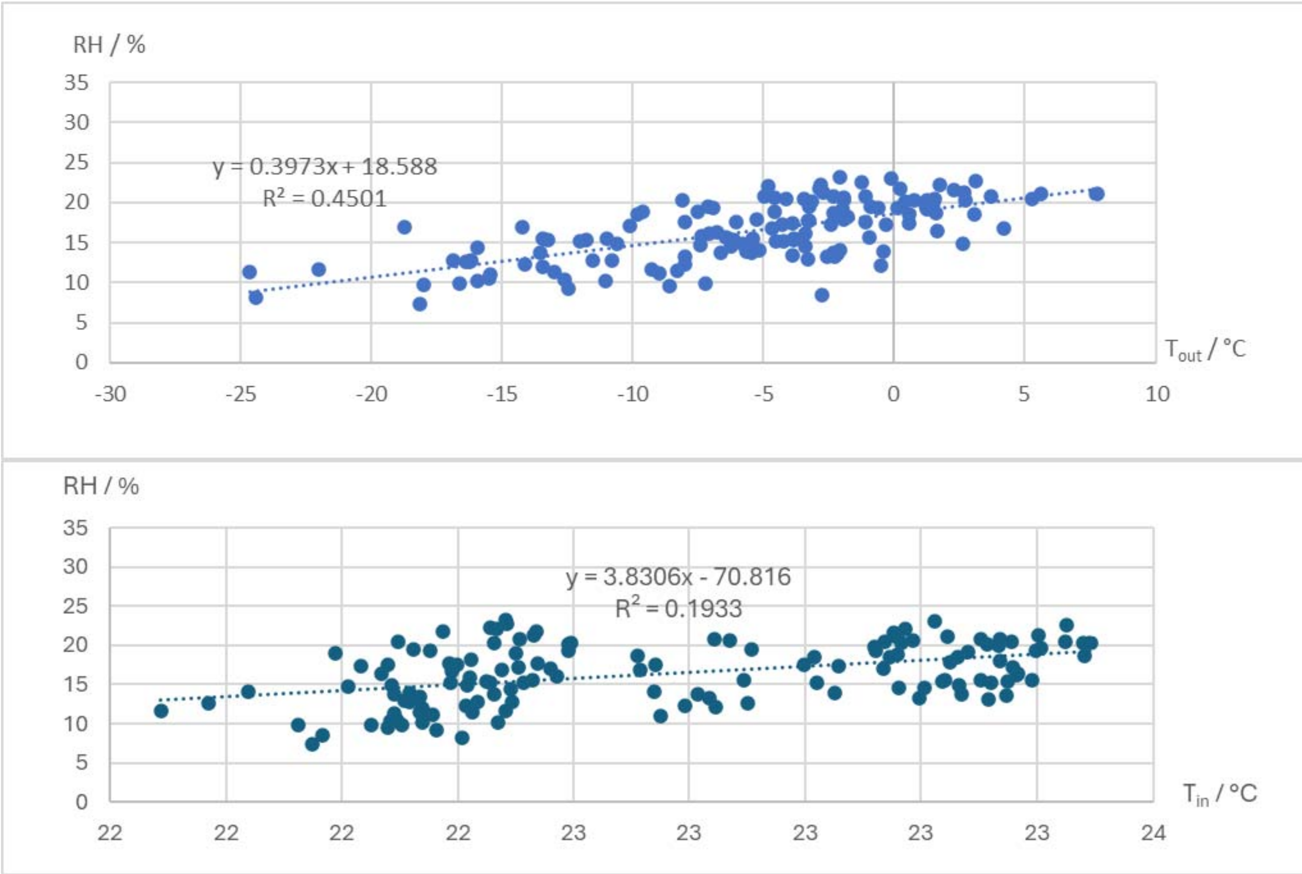

Figure 30. Indoor relative humidity vs outdoor temperature (top graph) and indoor relative humidity vs indoor temperature (Bottom graph) for Building X located in Luleå.

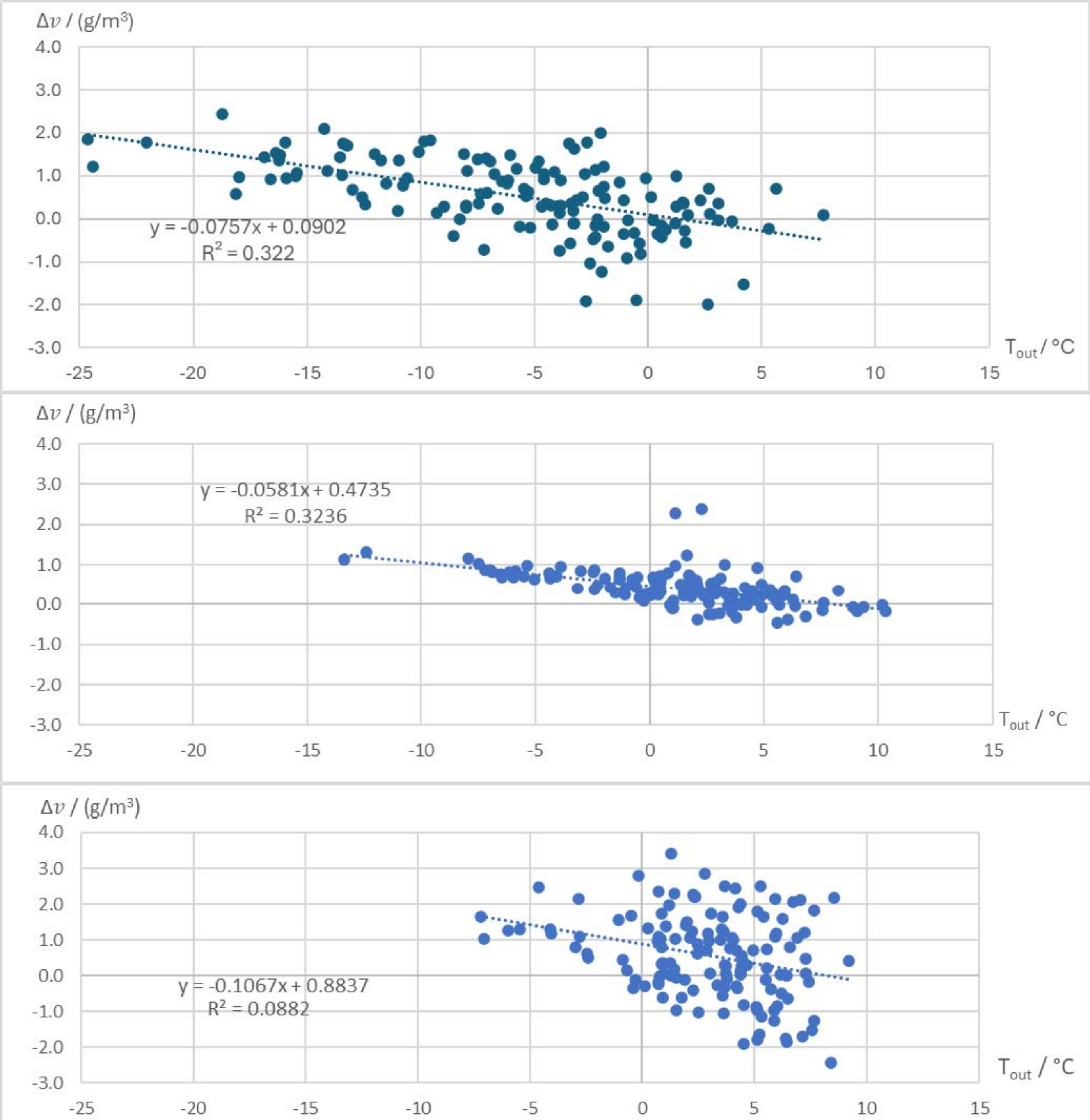

Figure 31 Moisture supplies for building X, building Y and building Z respectively.

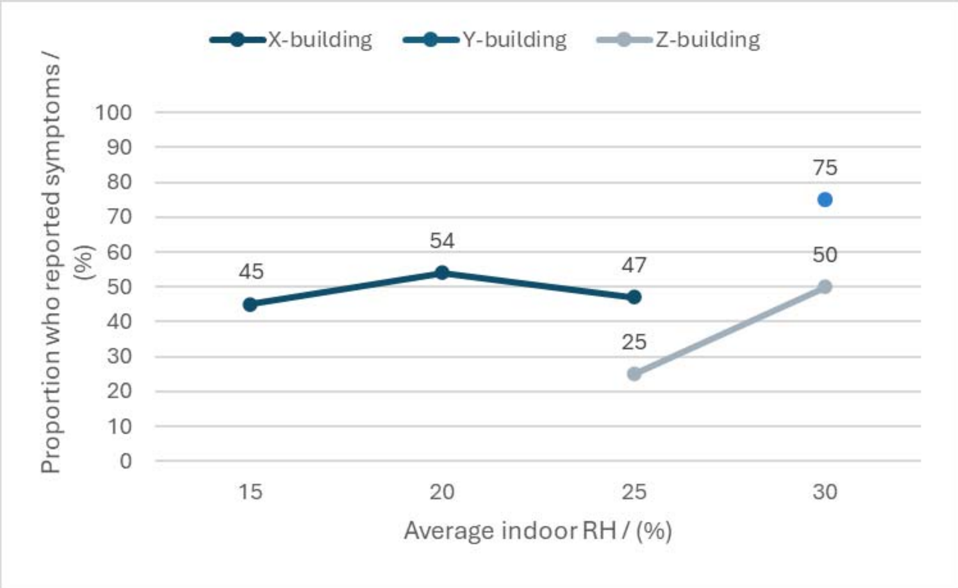

Figure 32. The corellation between the average indoor RH and fraction of reported symptoms related to the occupants in the elederly homes.

3.3.2 Low Indoor Relative Humidity and Indoor Climate: Health Effects and Microorganism Survival

The thesis (Han, 2021) combines a structured literature review and simple hygro-thermal calculations to understand how low indoor relative humidity (RH) affects human health and the survival and transmission of common microorganisms relevant in Nordic buildings (influenza virus, rhinovirus/common cold, norovirus/winter vomiting disease, and Legionella). The work further explores the role of absolute humidity (AH; g/m^3) and discusses when humidification may be warranted within moisture safety constraints.

The thesis is a literature review primarily based on LUBsearch and Google Scholar. Studies were selected to represent both objective clinical measurements (tear film stability, nasal cavity metrics, skin hydration, laboratory virus survival) and subjective reports (questionnaires in offices and schools). Hygro-thermal relationships were summarized using the standard definition of RH (ratio of actual to saturation water vapor) and the polynomial saturation curve used in Scandinavian building research. Simple steady-state calculations and duration analyses (varaktighetsdiagram) were produced for Malmö, Stockholm, and Kiruna to estimate indoor RH given outdoor vapour content and typical moisture generation (vms) and ventilation rates. Figure 33 gives vapor ratio.

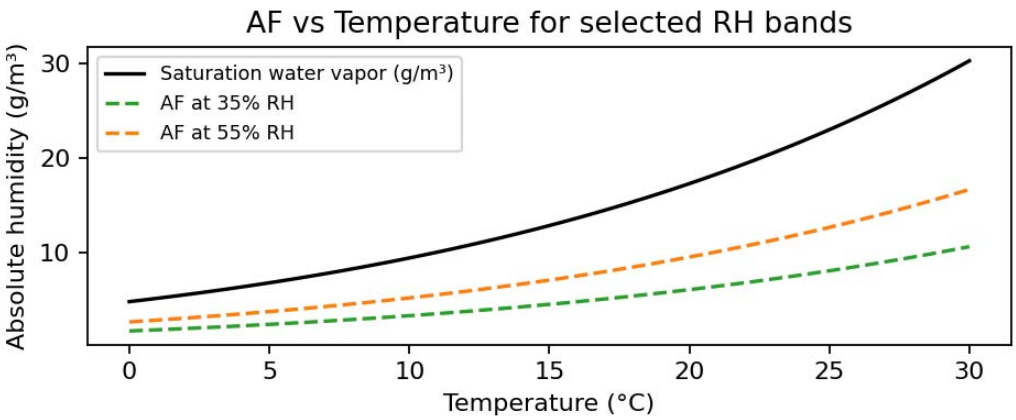

Figure 33. Absolute humidity (vapour content) versus temperature for selected RH bands (35% and 55%) using the saturation polynomial reported in the thesis. This illustrates that vapour content is temperature-dependent while RH is a fraction of saturation.

Across human studies, low RH (typically ≤30–35%) is consistently associated with increased complaints of "dry air", ocular irritation, reduced tear film stability, nasal dryness, and skin symptoms. Controlled interventions raising RH from the mid-20s to ~40–50% reduced ocular dryness and nasal symptoms and modestly improved perceived air quality and task performance. In clinical chamber exposures, older adults showed greater nasal mucosa dryness under low RH than younger adults. Laboratory animal models (mice) confirmed corneal damage and reduced tear production at ~15% RH.

Microorganism survival showed organism-specific patterns. Influenza transmission efficiency in animal models is highest at low RH and low temperature (e.g., 20–35% RH at 5–20°C) and declines as RH rises to ~50%; some rebound occurs at very high RH, while at ~80% RH aerosol removal increases due to droplet growth and settling. For rhinovirus, survival is short at low-to-mid RH but substantially prolonged at high RH (≥75%). Norovirus proxies (murine norovirus) indicate better survival at low AH/low temperature; survival declines above ~12 g/m³ AH. Legionella growth is favoured in warm, wet systems; aerosol transmission risk correlates with warm, humid ambient conditions, while survival in air is lower around ~50–60% RH.

The thesis calculations suggest that in Nordic climates, indoor RH during the heating season often falls below 35% given typical ventilation and moisture generation, especially in northern cities. Duration analyses can identify the fraction of occupied hours below target RH, guiding whether limited, well-controlled humidification may be justified without exceeding a 3 g/m³ indoor moisture addition guideline. See results in Figures 34-35.

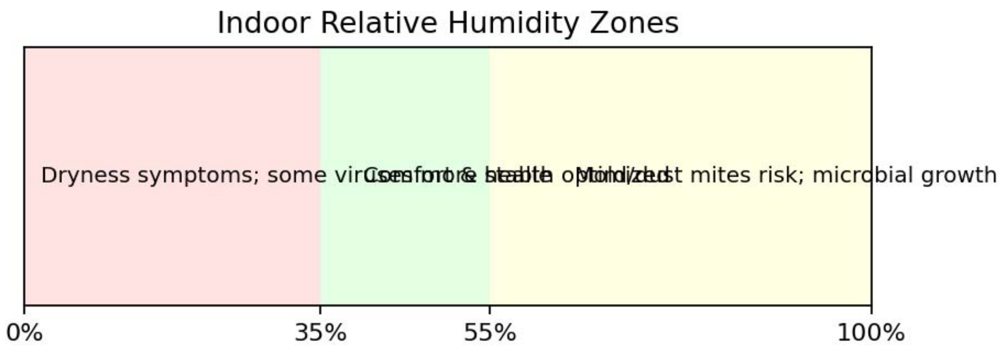

Figure 34. Conceptual indoor RH zones: ≤35% (dryness symptoms; some viruses more stable), 35–55% (comfort band), ≥55% (microbial growth risks such as mold and dust mites increase).

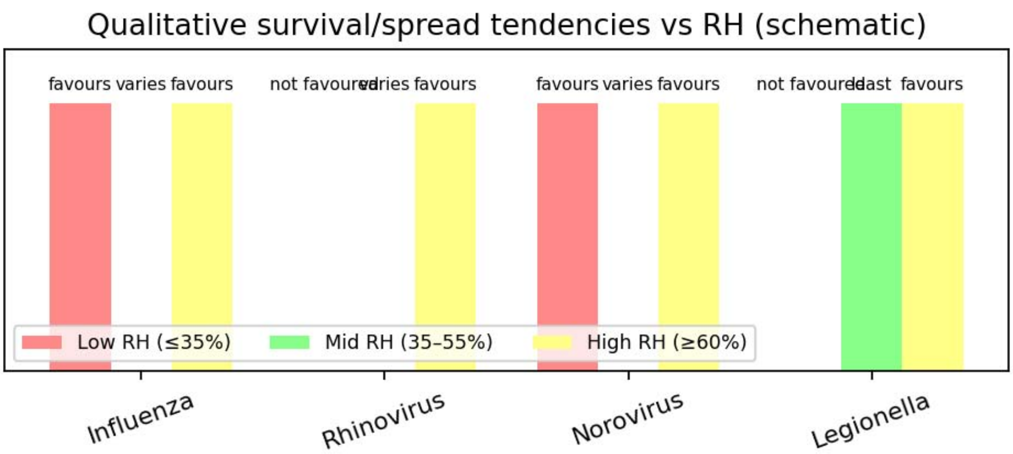

Figure 35. Schematic tendencies of survival/spread versus RH across key organisms discussed in the thesis (qualitative summary from cited studies).

The convergence of clinical, questionnaire, and laboratory evidence supports maintaining indoor RH in a moderate band to reduce dryness-related symptoms and limit favourable conditions for certain respiratory viruses. However, microbial risks at higher RH (mould, dust mites, and some enteric viruses) and water system pathogens (Legionella) necessitate careful moisture management. A key methodological point in the thesis is the use of AH (g/m³) as a more direct determinant of aerosol physics and virus stability than RH alone, because RH varies with temperature. In practice, RH remains useful for human comfort control since occupants experience temperature and RH jointly.

Humidification should be targeted, time-limited to occupancy, and capped by moisture safety guidance (e.g., ≤3 g/m³ addition) with rigorous design, commissioning, hygiene, and maintenance to prevent microbial amplification in humidification equipment or building assemblies. The thesis highlights that perceived "dry air" can also reflect chemical and particulate irritants; thus source control and ventilation quality are foundational alongside humidity control.

Based on the reviewed studies, an indoor RH range of approximately 35–55% is broadly optimal for human comfort and health. RH should generally be kept ≥35% to mitigate dryness symptoms, while avoiding sustained RH ≥60% to limit risks of mold and dust mites. Absolute humidity is a better metric for analysing microorganism survival, whereas RH is practical for occupant comfort control. In Nordic heating seasons, limited, well-managed humidification may be warranted to reach ~35–45% RH in selected buildings, provided moisture safety (≤3 g/m³ addition), hygiene, and system maintenance are ensured.

3.3.3 Impact of Green Walls on Indoor Air Humidity - A case study of a medium-sized office building in Malmö, Sweden

This summary synthesizes findings (Trejo Montes, 2023) from a case study evaluating the effect of an indoor Green Wall (GW) on air humidity in a medium-sized office building in Malmö, Sweden. The study addresses low indoor humidity during cold seasons and explores whether GW technology can improve indoor air quality and occupant comfort without major energy penalties. The research builds on literature linking humidity to health, comfort, and infection risk, and positions GW as a passive design measure complementing mechanical ventilation.

Measurements were conducted over 27 weeks (September 2021 - April 2022) using sensors integrated with the air handling unit (AHU) and additional calibrated loggers. The office was divided into three zones; the GW was installed in a common area (Zone 2). Data included outdoor and indoor temperature, vapor ratio (g/kg), and airflow (l/s). Weekly averages before and after GW installation were compared under similar outdoor conditions. Calibration against a climate chamber ensured accuracy. The GW measured 2.1 × 3.8 m² (≈ 8 m²), irrigated daily with ~12 l water, and contained indoor plant species suited for low to medium light. Figure 36 shows the set up.

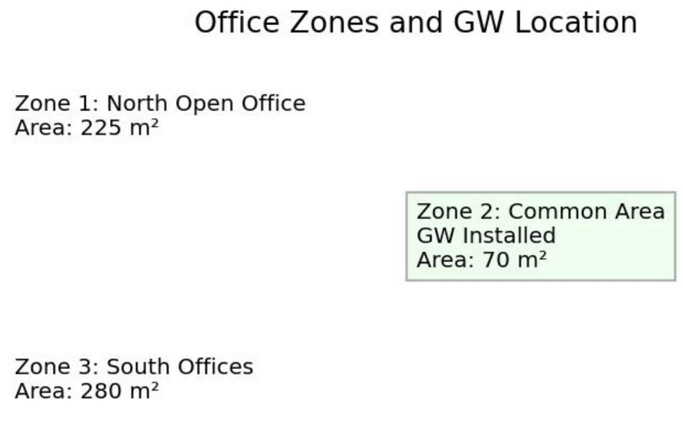

Figure 36. Schematic representation of office zones and GW location.

Before GW installation, the vapor ratio difference (xRoom - xSupply) averaged - 0.286 g/kg, indicating the room was drier than supply air. After GW installation, differences became positive, ranging from 0.41 g/kg to 0.64 g/kg, with peaks near 1 g/kg under outdoor temperatures of °C 4 to 6 °C. This suggests a measurable humidity contribution from the GW. Zone comparison showed higher vapor ratio differences near the GW (Zone 2) than in remote areas (Zone 1), confirming localized impact. CO_2 levels remained similar (~460 ppm), indicating comparable occupancy. Figures 37-38 summarizes the result.

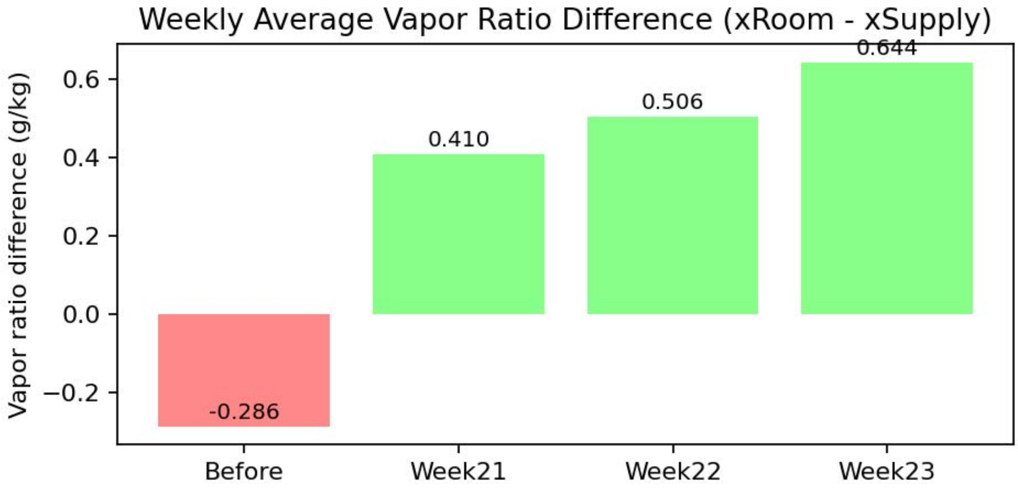

Figure 37. Weekly average vapor ratio difference before and after GW installation.

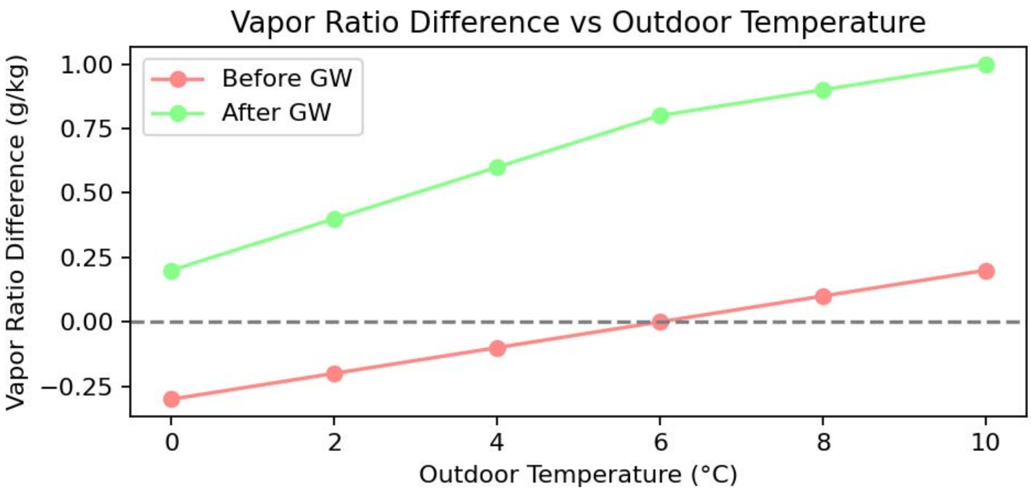

Figure 38. Vapor ratio difference vs outdoor temperature before and after GW installation.

The GW installation provided a modest but consistent increase in indoor humidity during winter, supporting its potential as a passive strategy for improving indoor air quality. Limitations include irrigation irregularities, plant species variability, and building airtightness assumptions. Outdoor conditions and ventilation settings constrained the number of comparable weeks. While the humidity gain (0.5 g/kg to 1 g/kg) is small relative to mechanical humidification, it may reduce dryness complaints and improve comfort without significant energy use. Integration with HVAC and careful maintenance are essential to ensure performance and avoid microbial risks.

The case study demonstrates that an indoor GW can positively influence indoor humidity under Nordic winter conditions. Although the effect is localized and moderate, GW technology may complement energy-efficient building design and enhance occupant well-being. Future research should explore long-term performance, species selection, and combined effects on thermal comfort and IAQ.

3.4 Different actual measurement profiles

Moisture supply for dwellings can be described on different time resolutions. A constant value is used in some of the results here, while 602 real profiles of measured dwelling years are used in some cases. In Figure 39-41, there is a comparison between using a constant moisture supply over the year compared to using the 602 profiles as a function of average moisture supply over the year. It can be seen that at higher moisture supplies, very uncommon I practical dwellings, there is a deviation that can be explained by moisture supply having different values on different seasons. The deviation starts to occur when condensation is more remarkable.

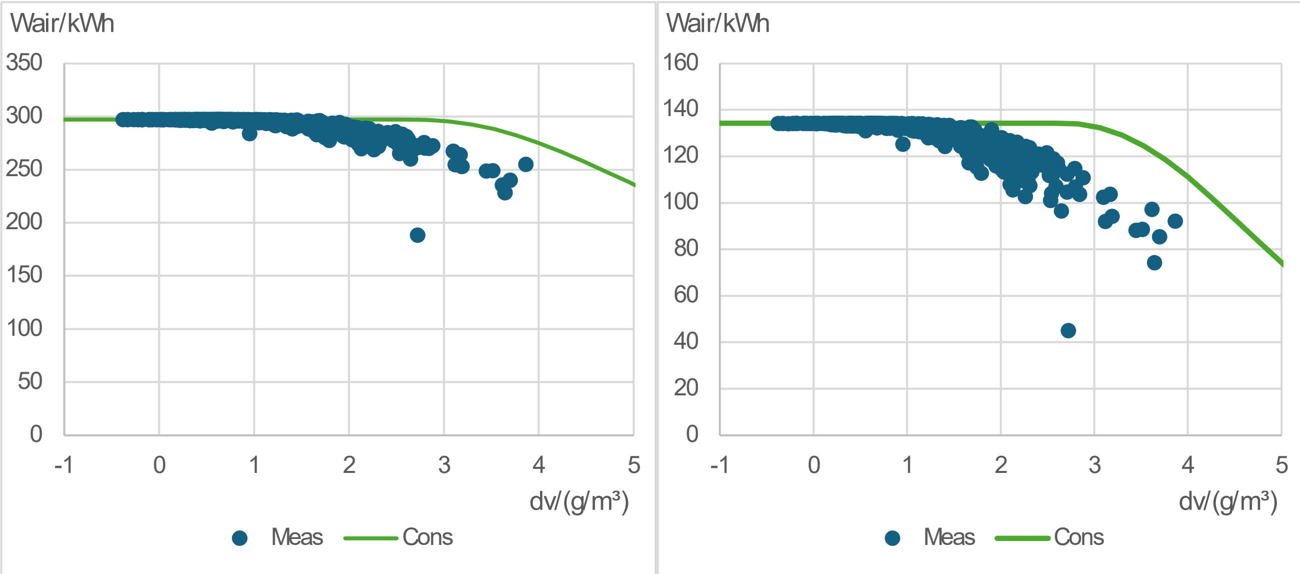

Figure 39. Air heating for default parameters with a nominal temperature efficiency of 78%, an exhaust temperature not going below 0°C and a heat recovery that cannot be controlled. Båstad outdoor climate is shown to the left and Nikkaluokta outdoor climate to the right. ”Meas” refers to the 602 measured dwelling-years of while “Cons” uses a constant moisture production resulting in a constant moisture supply.

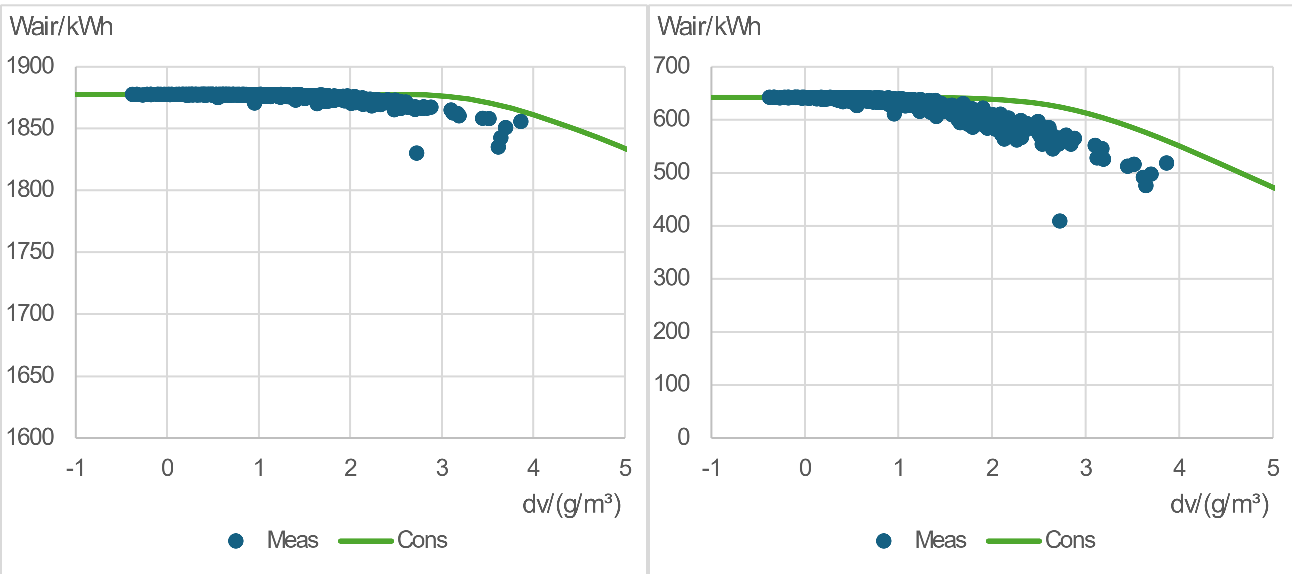

Figure 40. Air heating for default parameters with a nominal temperature efficiency of 83%, frosting protection for rotary wheels and a moisture recovery of 10 % and an increased airflow to 39 l/s to receive the same moisture supply as without moisture recovery. The heat recovery can be controlled. Båstad outdoor climate is shown to the left and Nikkaluokta outdoor climate to the right. ”Meas” refers

to the 602 measured dwelling-years of while "Cons" uses a constant moisture production resulting in a constant moisture supply.

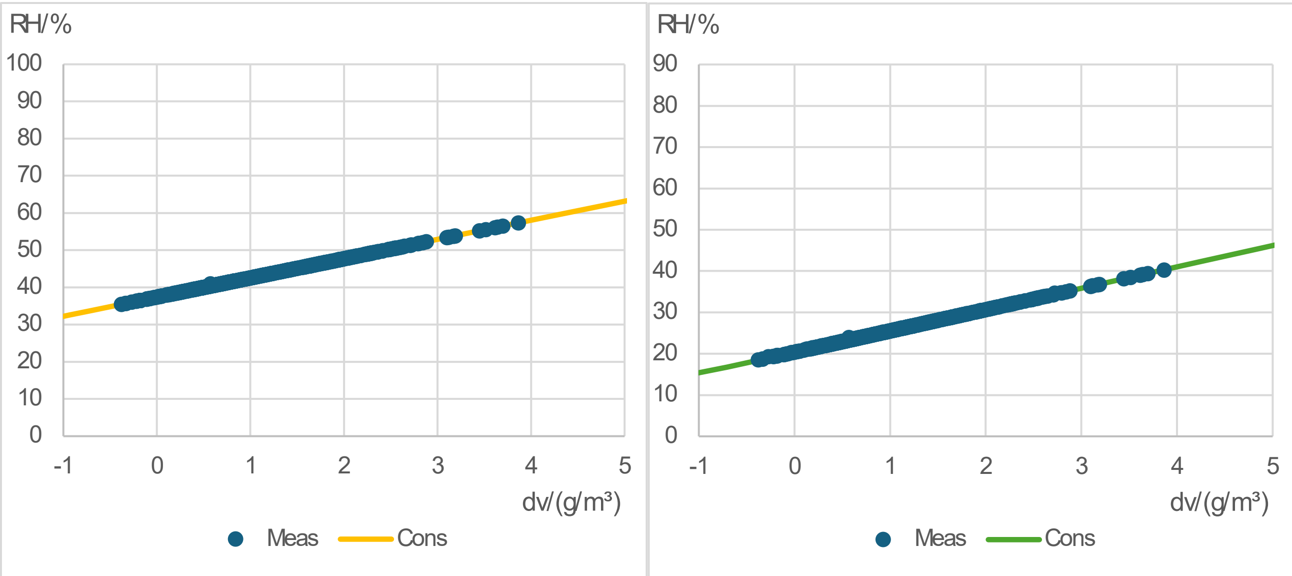

Figure 41. The resulting relative humidity as a function of moisture supply. Båstad outdoor climate is shown to the left and Nikkaluokta outdoor climate to the right. "Meas" refers to the 602 measured dwelling-years of while "Cons" uses a constant moisture production resulting in a constant moisture supply.

Figures 42-52 shows several resulting parameters for all included outdoor climates from 66 220 simulations. All results are presented as duration graphs for the 602 different dwelling years of measured moisture supply. Below is a list of explanations of the systems referred to for each curve. All given flows, q, has been increased one step in the legend due to a macro bug. They refer to airflows given below. In systems 6, 7 and 8 the flow, q, has been increased to give the same moisture supply as if there were no moisture recovery. The moisture recovery is varied for the rotary wheel values.

1:p,q35	Plate geatr exchanger. Eta_nom = 0.78. q = 35 l/s. mr = 0
2:r,m0,q35	Rotary wheel. Eta_nom = 0.83. q = 35 l/s. mr= 0
3:r,m0.1,q35	Rotary wheel. Eta_nom = 0.83. q = 35 l/s. mr = 0.1
4:r,m0.4,q35	Rotary wheel. Eta_nom = 0.83. q = 35 l/s. mr = 0.415
5:r,m0.8,q35	Rotary wheel. Eta_nom = 0.83. q = 35 l/s. mr = 0.8
6:r,m0.8,q175	Rotary wheel. Eta_nom = 0.83. q = 175 l/s. mr = 0.8
7:r,m0.4,q60	Rotary wheel. Eta_nom = 0.83. q = 60 l/s. mr = 0.415
8:r,m0.1,q39	Rotary wheel. Eta_nom = 0.83. q = 39 l/s. mr = 0.415
9:r,m0.1,v3	Rotary wheel. Eta_nom = 0.83. v_set = 3 g/m^3. mr = 0.1
10:r,m0,v3	Rotary wheel. Eta_nom = 0.83. v_set = 3 g/m^3. mr = 0
11:p,v3	Plate geatr exchanger. Eta_nom = 0.78. v_set = 3 g/m^3. mr=0

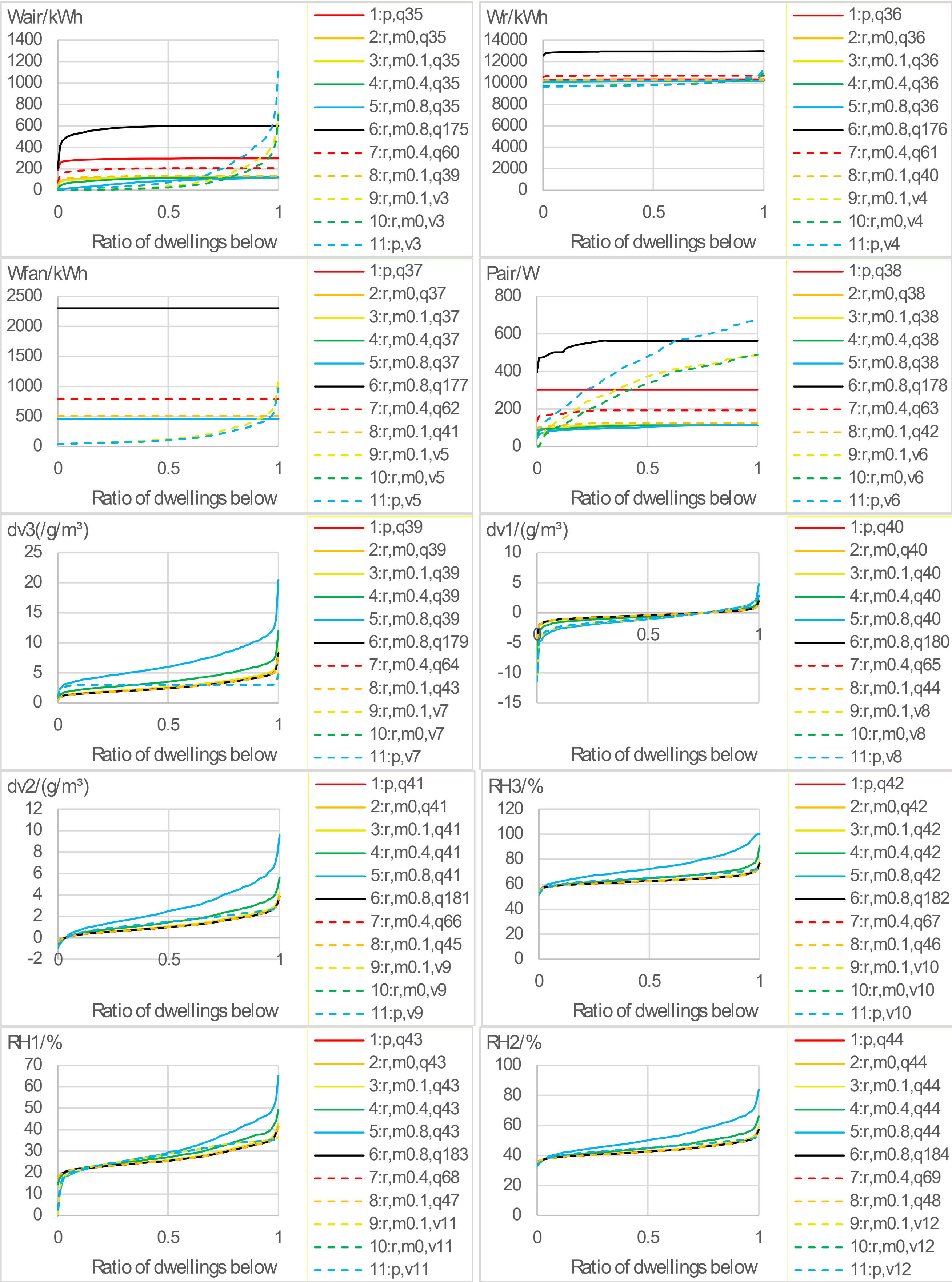

Figure 42. Results from the outdoor climate of Båstad, Sweden.

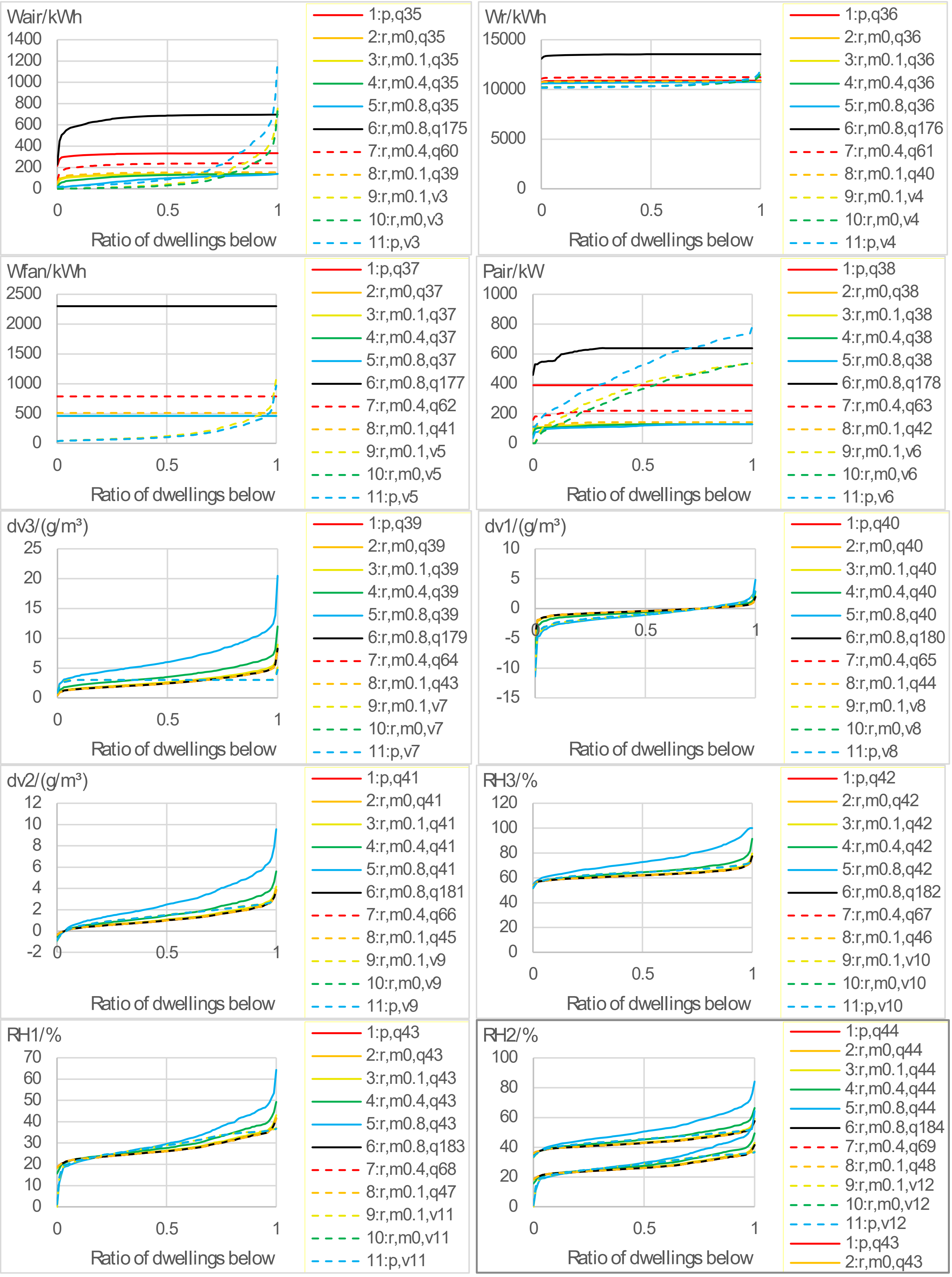

Figure 43. Results from the outdoor climate of Helsingborg, Sweden.

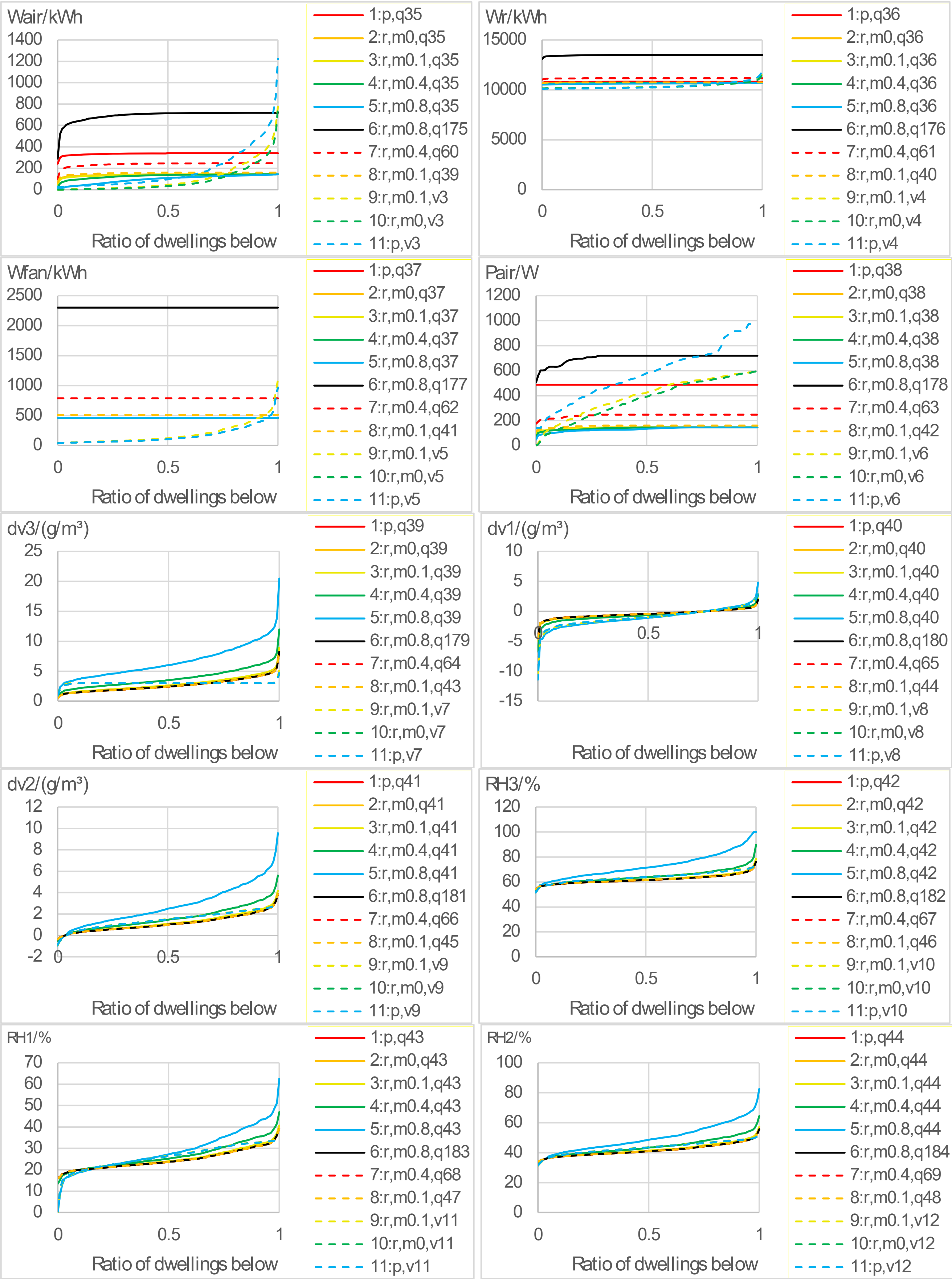

Figure 44. Results from the outdoor climate of Göteborg, Sweden.

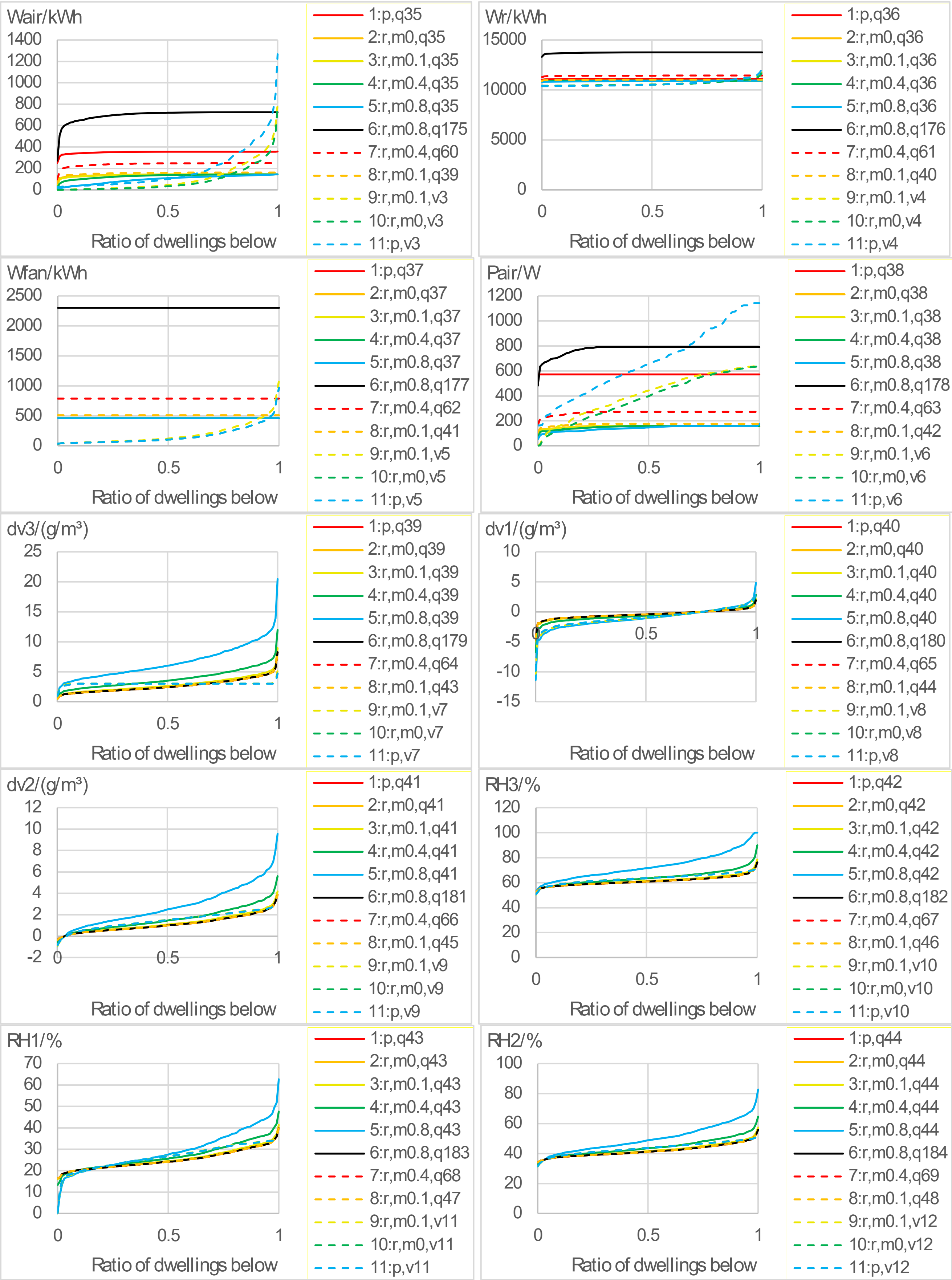

Figure 45. Results from the outdoor climate of Kalmar, Sweden.

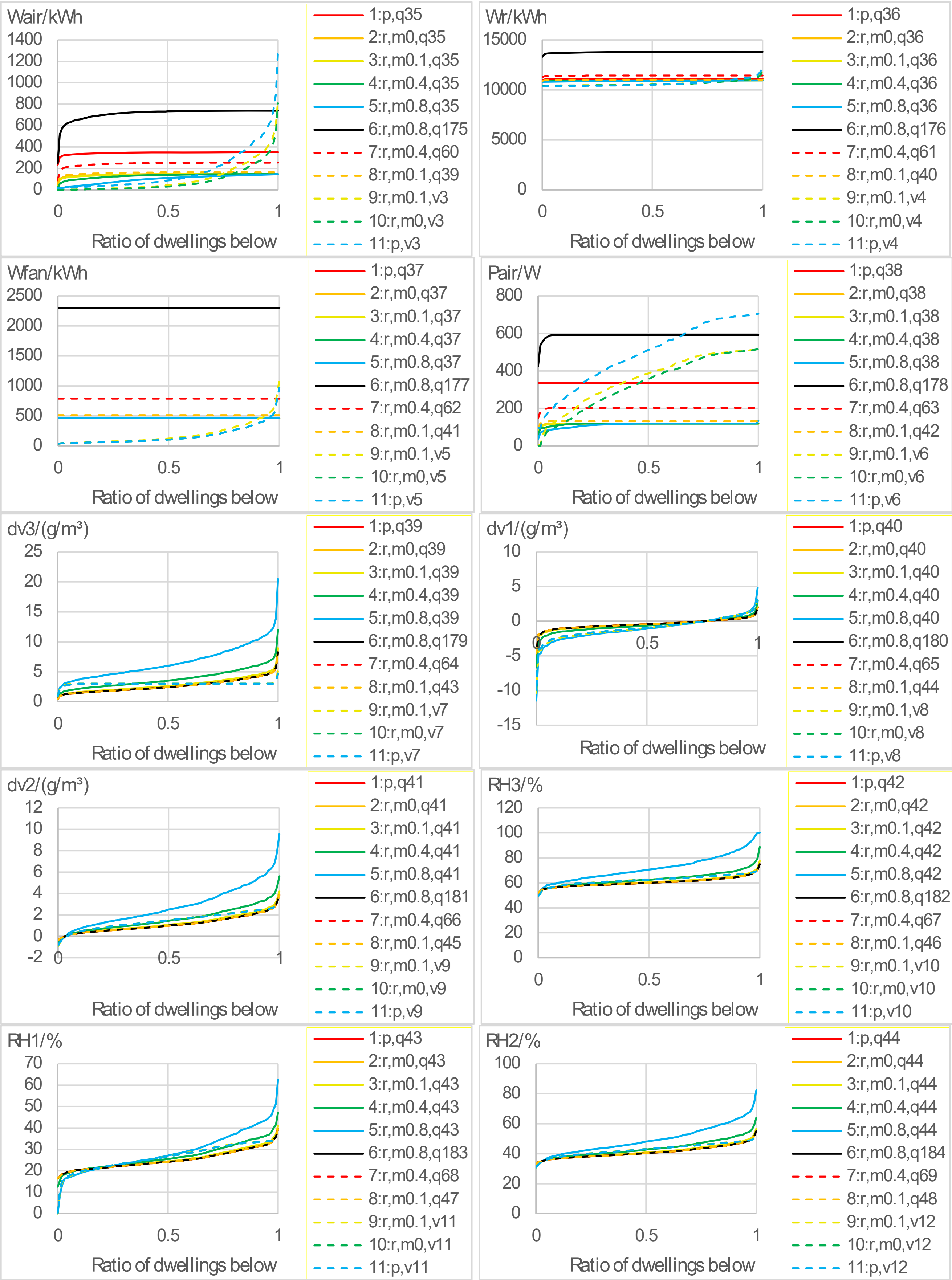

Figure 46. Results from the outdoor climate of Visby, Sweden.

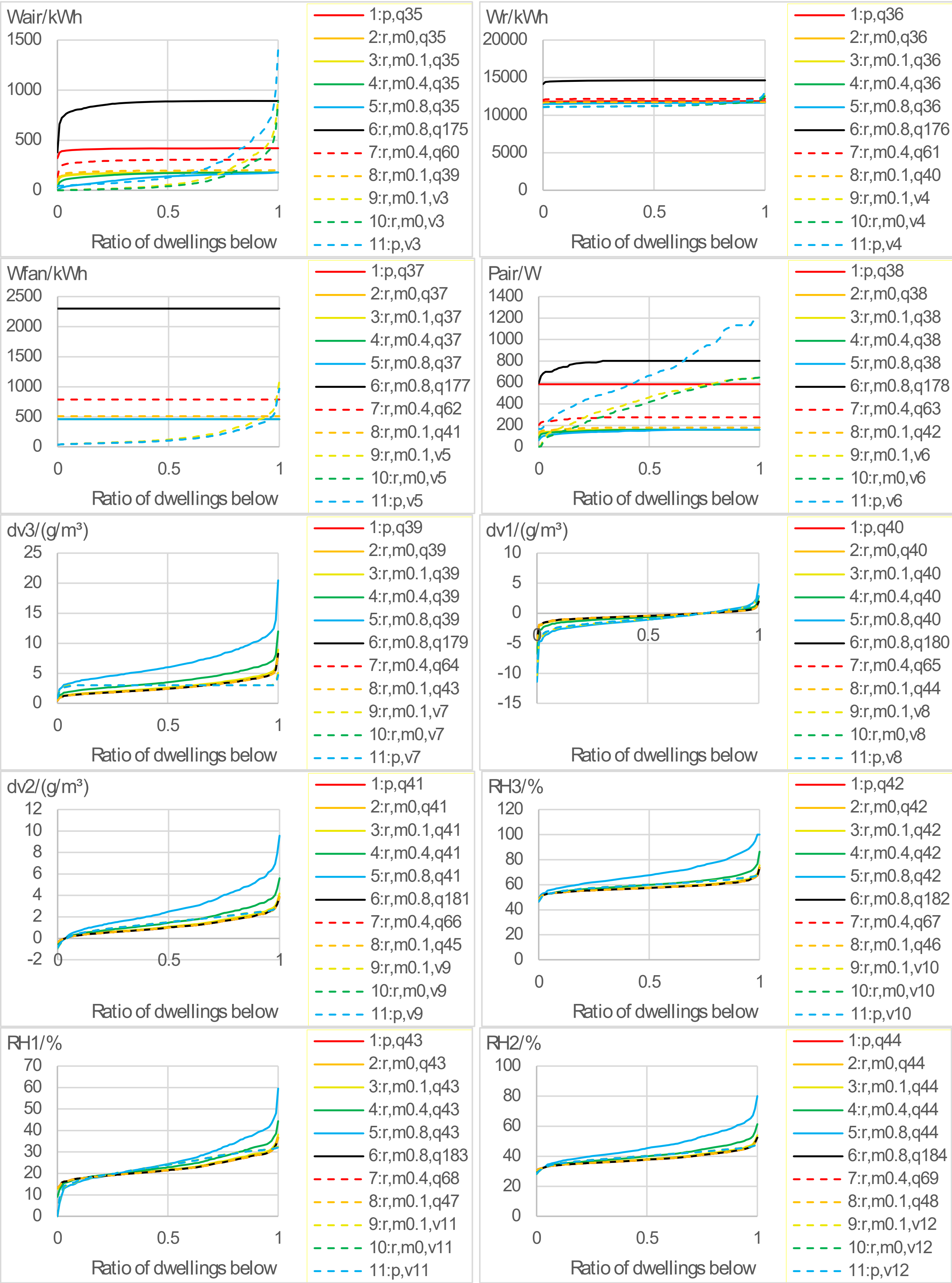

Figure 47. Results from the outdoor climate of Stockholm, Sweden.

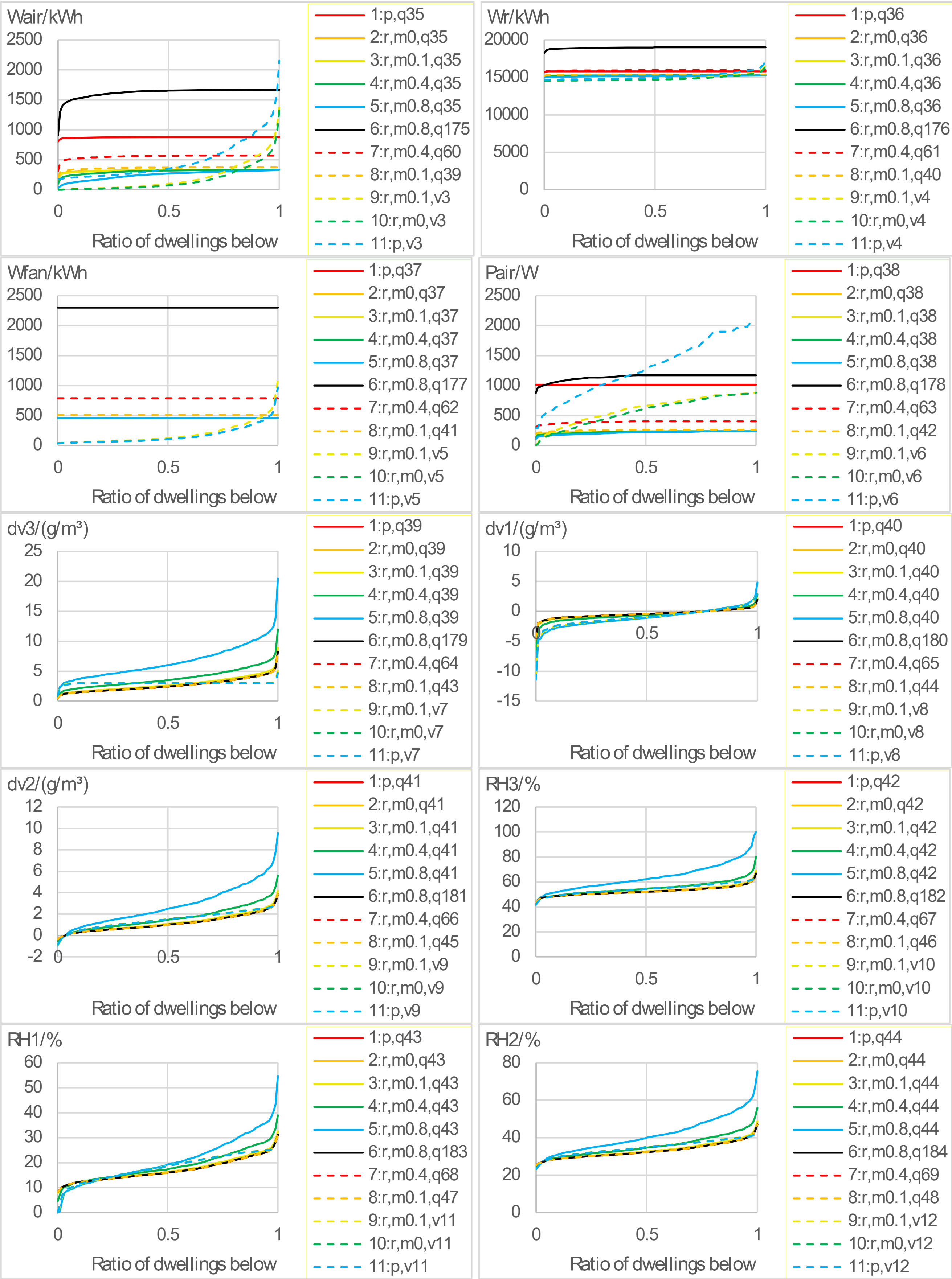

Figure 48. Results from the outdoor climate of Skellefteå, Sweden.

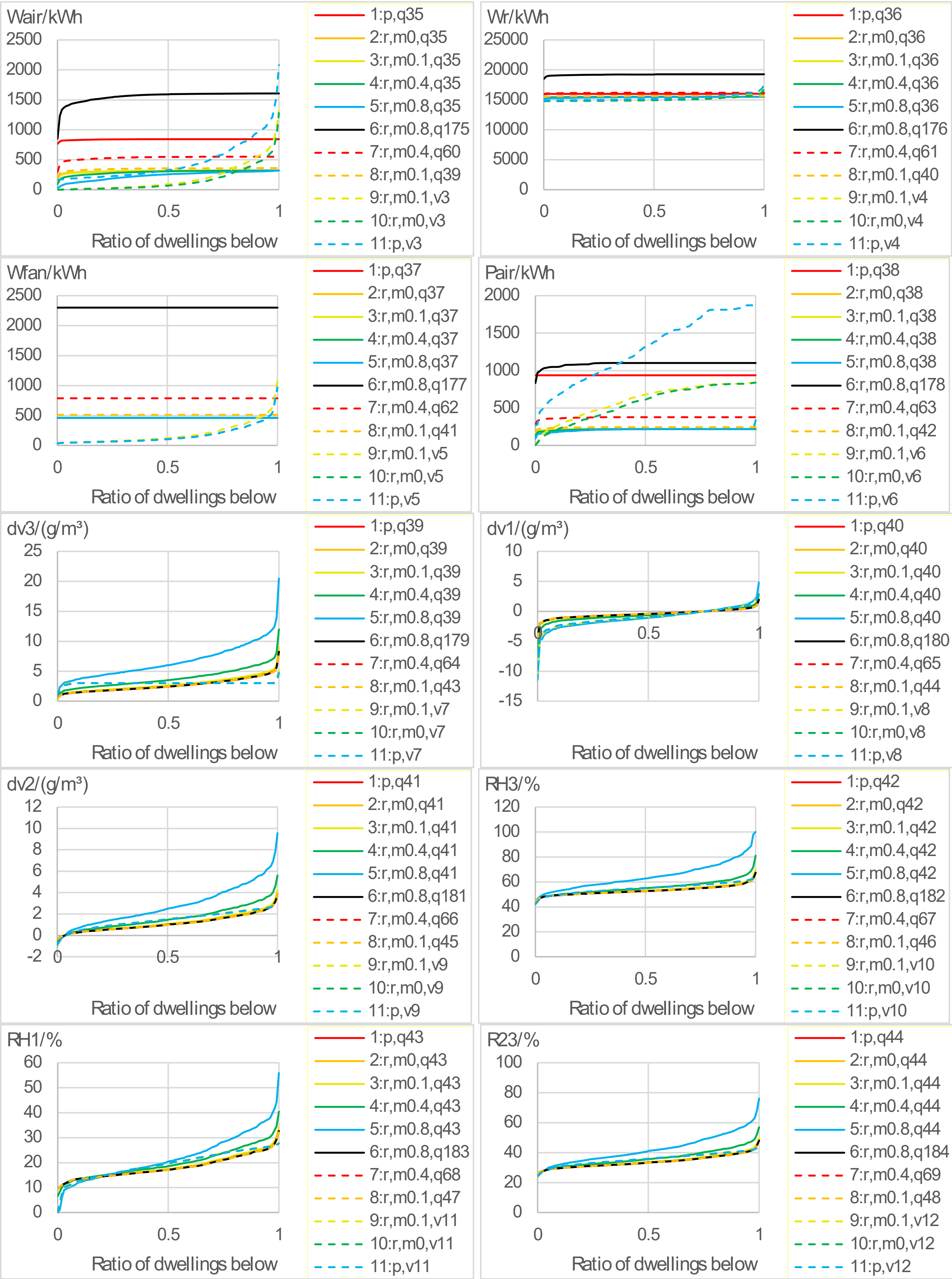

Figure 49. Results from the outdoor climate of Malung, Sweden.

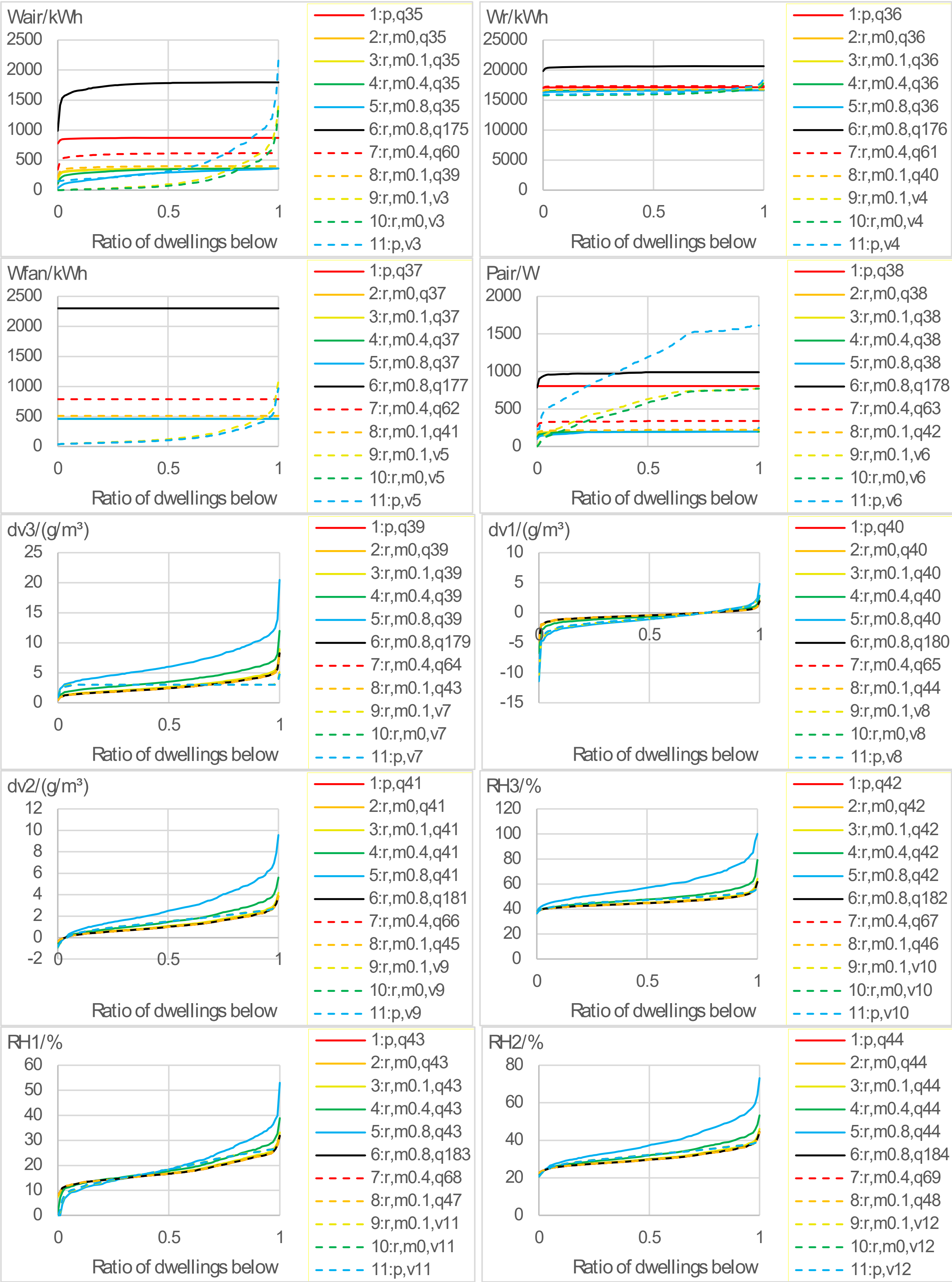

Figure 50. Results from the outdoor climate of Storlien, Sweden.

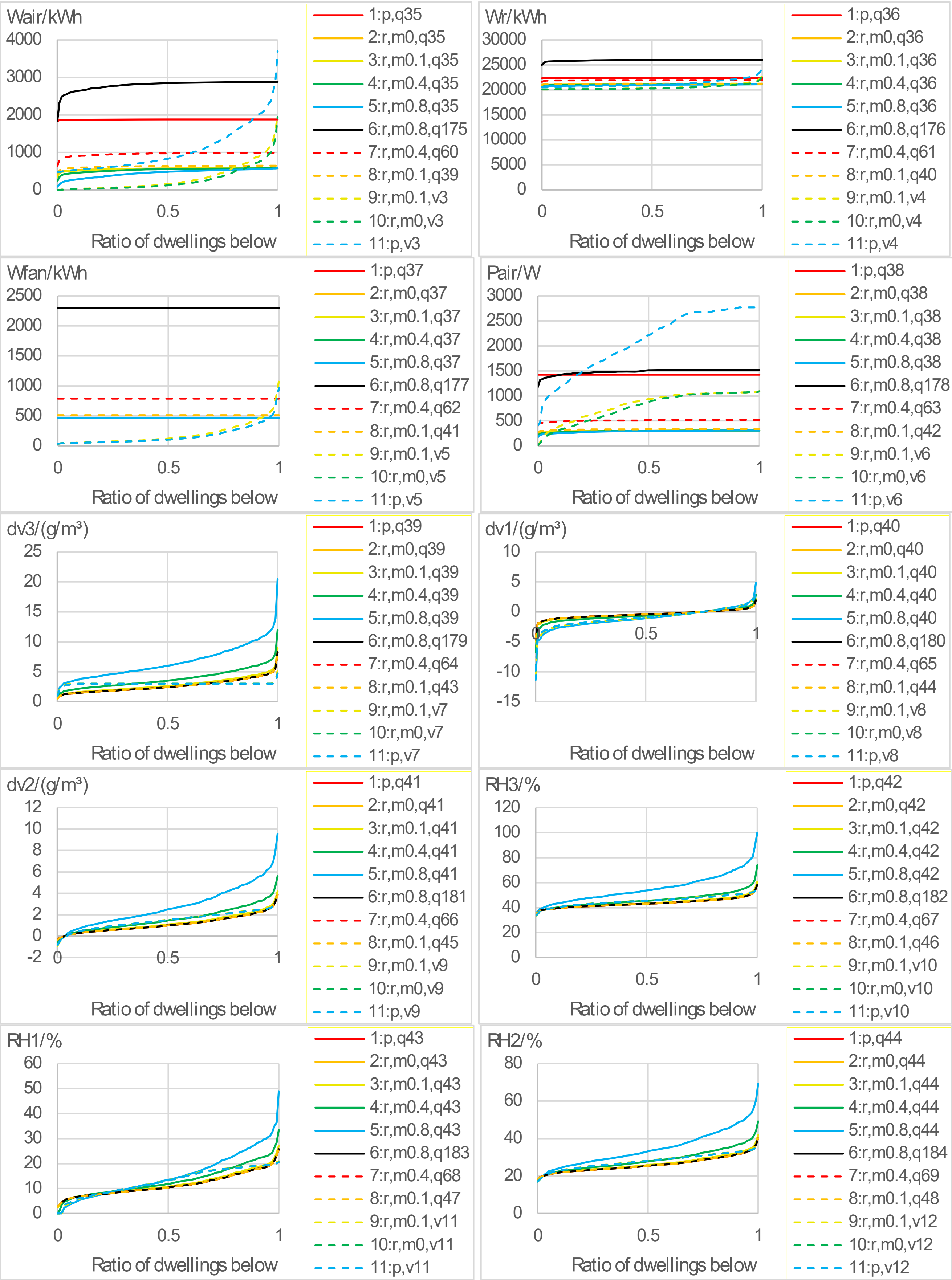

Figure 51. Results from the outdoor climate of Nikkaloukta, Sweden.

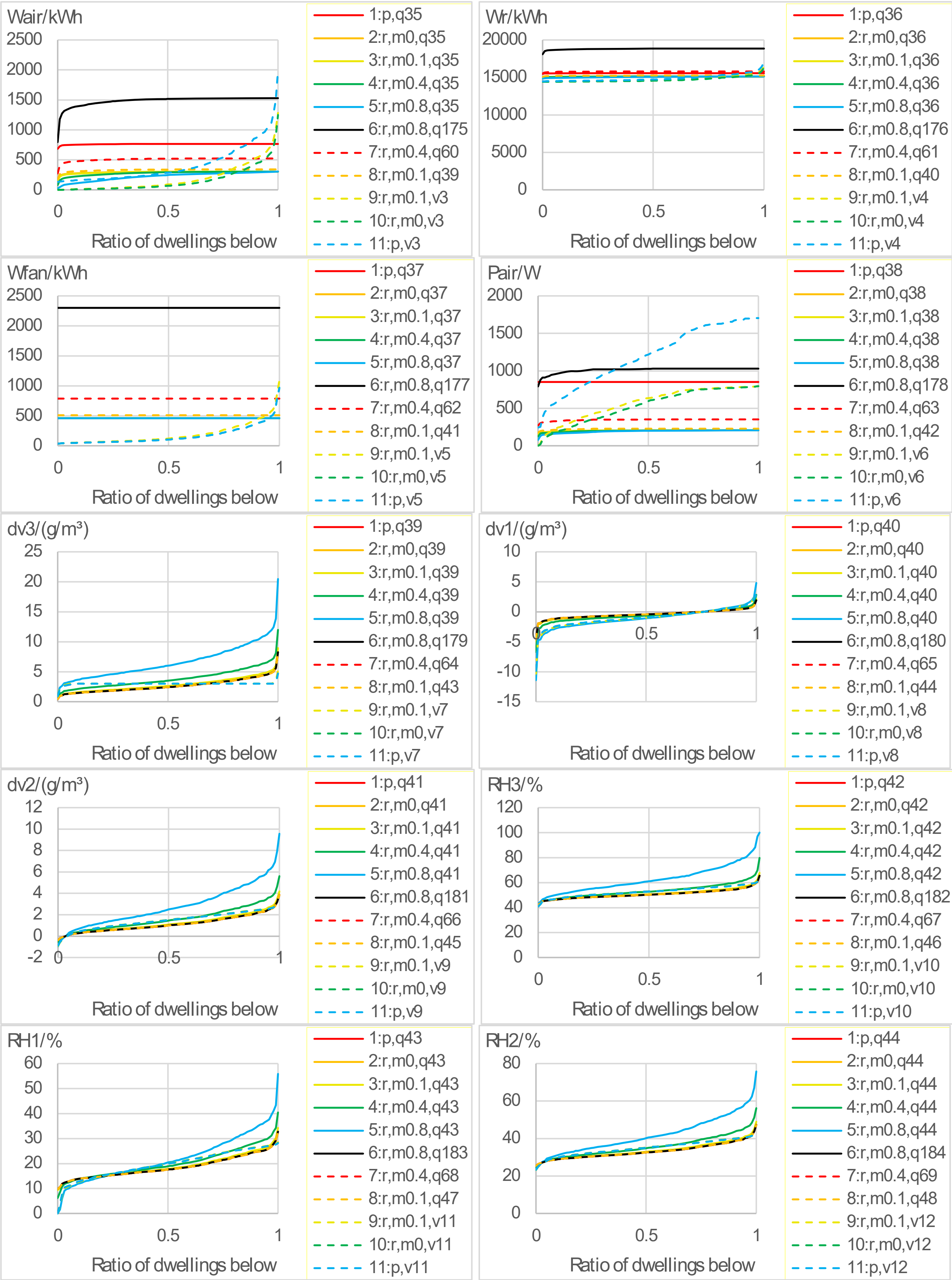

Figure 52. Results from the outdoor climate of Öresund, Sweden.

3.5 Parametric variation

In this chapter some parameters are varied for the input data. Figure 53-56 shows what happens if a constant moisture supply, dv, is varied for three types of heat exchangers with different eta_nom. “p” refers to plate heat exchanger with non controllable temperature efficiency and no allowed extract temperatures below 0 °C as frosting protection. “r” refers to a rotary wheel with controllable temperature efficiency and the rotary wheel model of frost protection. “rm” refers to a moisture recovery of 0.1 = 10 %, and in these cases the airflow, q, was increased to 39 l/s to give a corresponding moisture supply as a system without moisture recovery. The numbers refer to the eta_nom. In the total energy use, fan electricity is included to show the influence from the higher flow on the electricity use, but also with q_nom_SFP changed to 39 l/s.

In Båstad, looking at the toal energy a plate heat exchanger gives slightly lower value than a rotary one of the same eta_nom. This is explained by the controllable temperature efficiency of the rotary wheel scenario where added heating to the room can increase if the supply air temperature is kept back to t_sa. In Nikkaloukta, the amount of frost protection makes the rotary wheel much better.

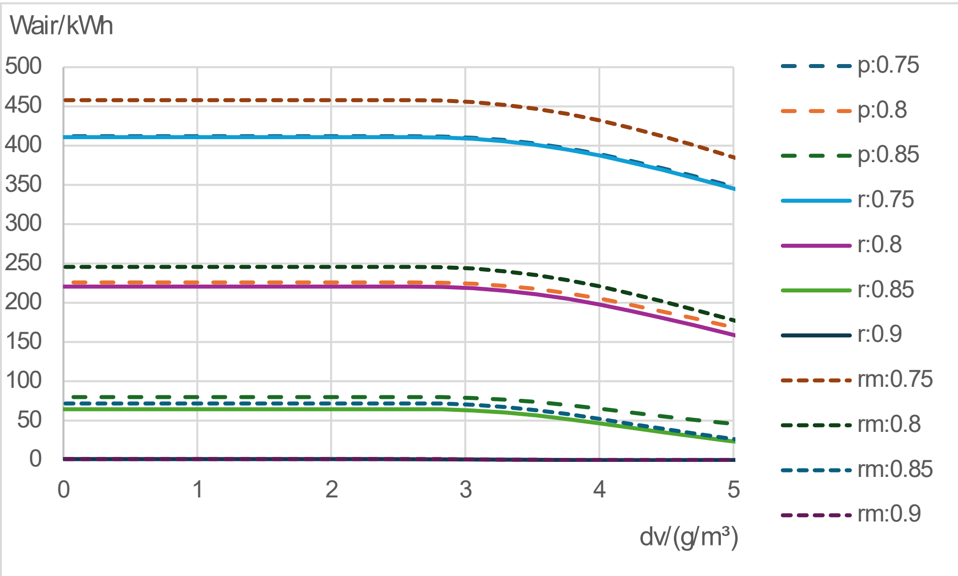

Figure 53. The air heating use as a function of a constant moisture supply for different heat exchanger set ups in the outdoor climate of Båstad.

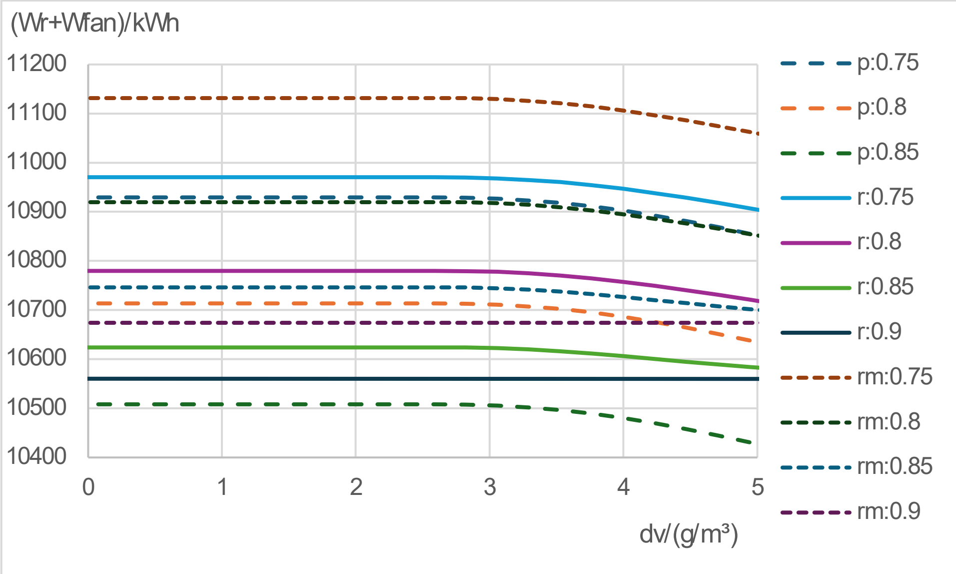

Figure 54. The total energy use as a function of a constant moisture supply for different heat exchanger set ups in the outdoor climate of Båstad.

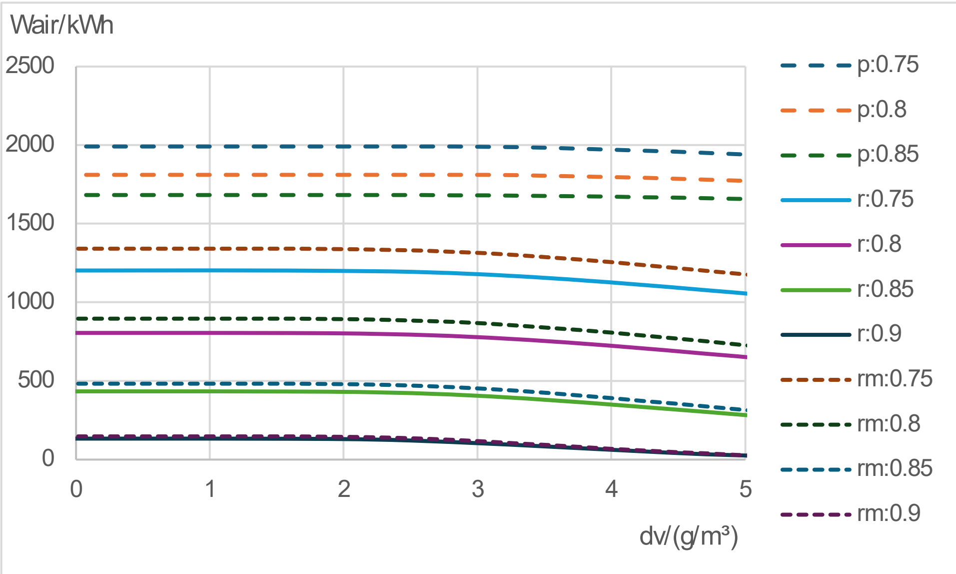

Figure 55. The air heating use as a function of a constant moisture supply for different heat exchanger set ups in the outdoor climate of Nikkaloukta.

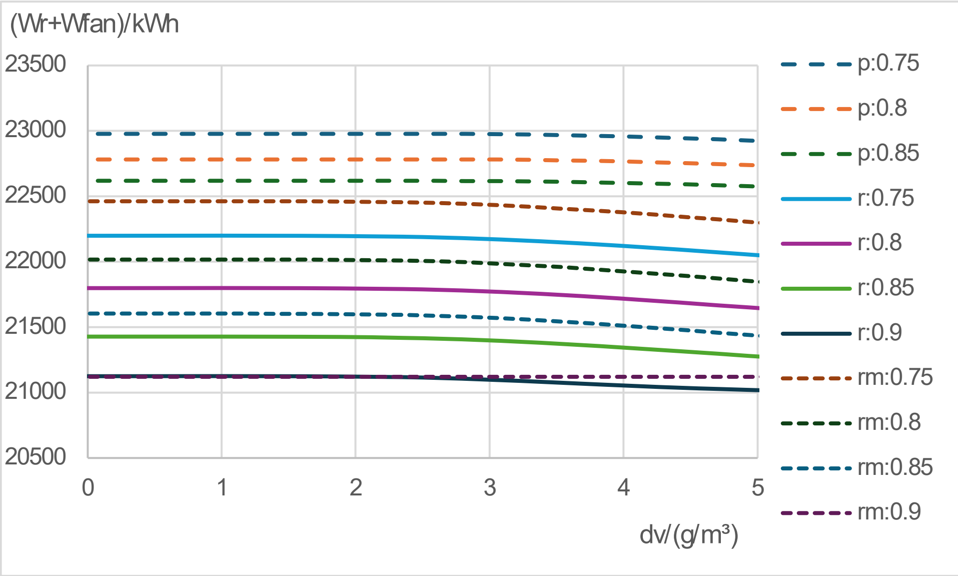

Figure 56. The total energy use as a function of a constant moisture supply for different heat exchanger set ups in the outdoor climate of Nikkaloukta.

Figure 57-58 shows the lower percentiles of the resulting relative humidity for different levels of moisture recovery, mr. This was for a rotary wheel with eta_nom = 0.83 and the frost protection of the rotary wheel model. RH is low in Nikkaloukta in winter, and it can be increased with moisture recovery, but it is important to not reach too high levels other parts of the year, creating moisture risks for the building construction.

Figure 59 shows the result from the same setup as in Figure 57-58 when the airflow is controlled by the moisture supply with varying setpoint. Here a constant moisture supply is used as well as the linearly average described in Figure 22.

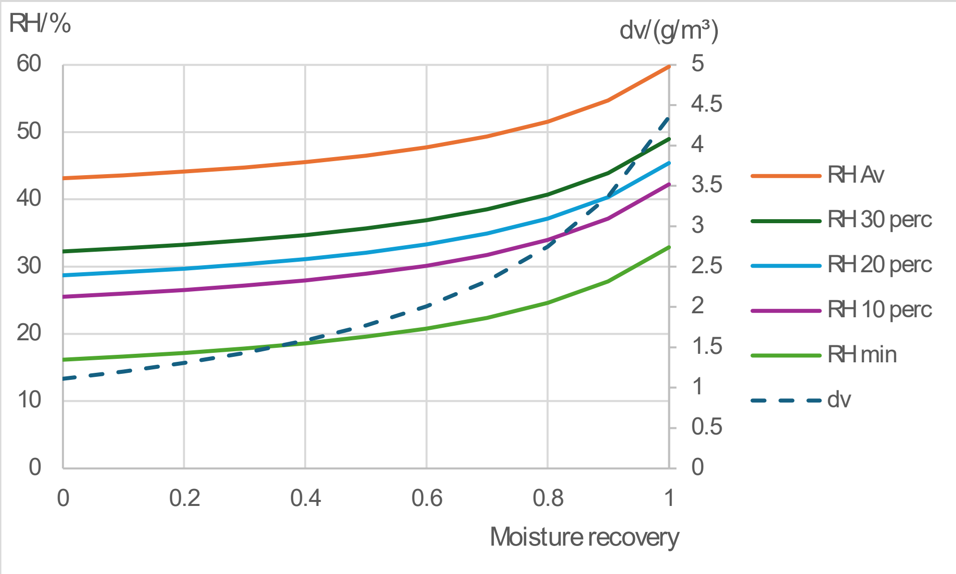

Figure 57. The resulting relative humidity profiles for different percentile and average together with resulting moisture supply for different moisture recovery in the outdoor climate of Båstad.

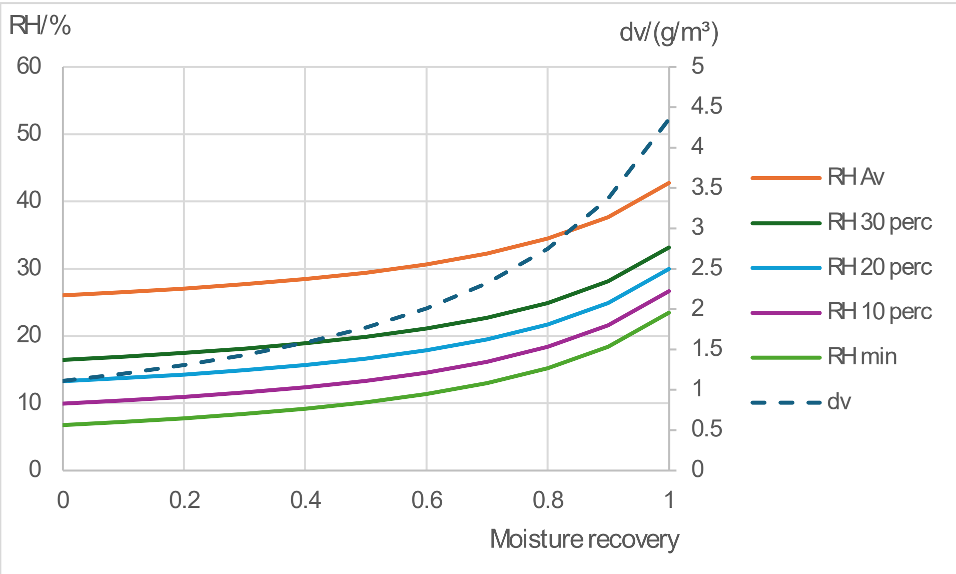

Figure 58. The resulting relative humidity profiles for different percentile and average together with resulting moisture supply for different moisture recovery in the outdoor climate of Nikkaloukta.

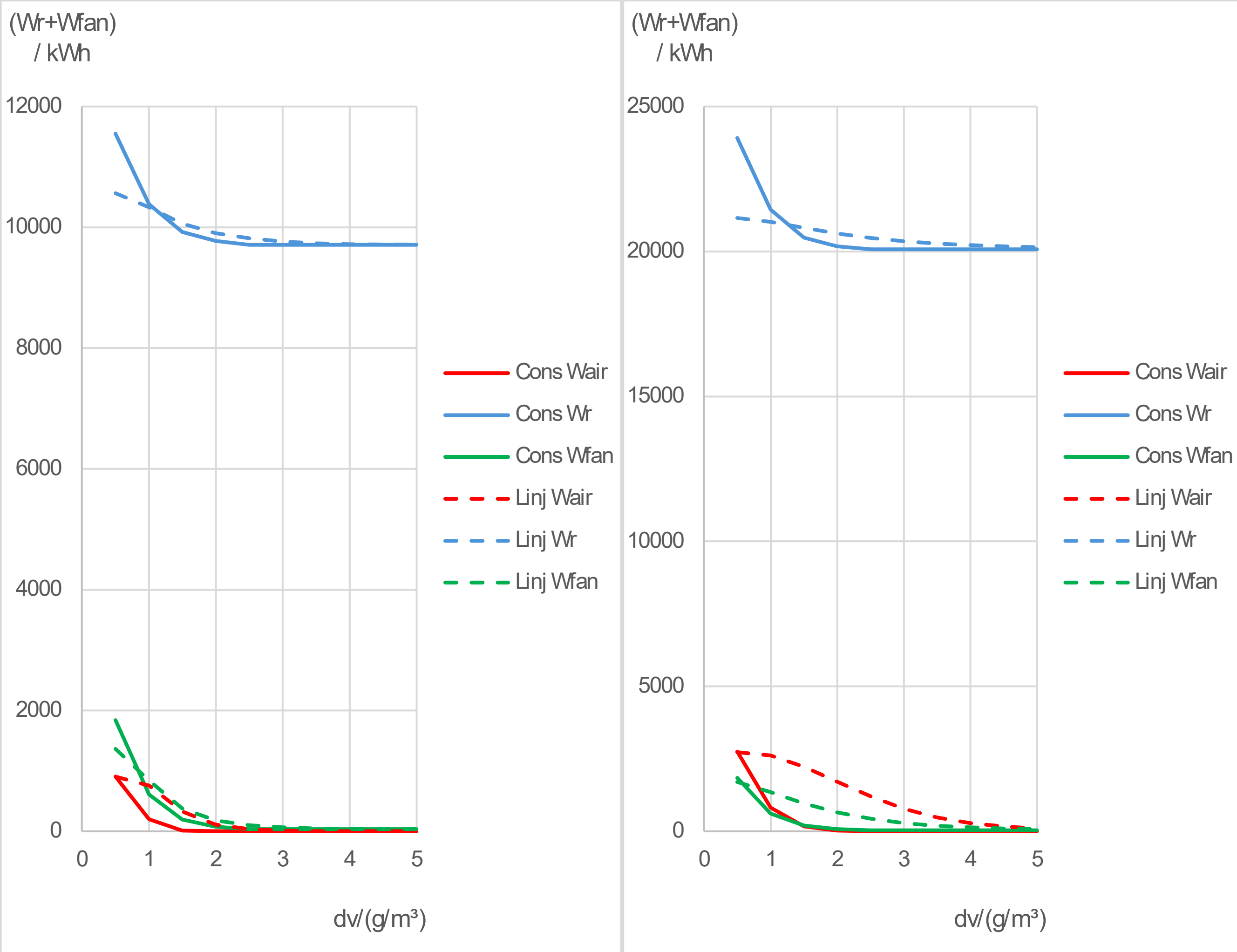

Figure 59. Varying the setpoint of a control based on moisture supply and resulting energies for Båstad outdoor climate to the left and Nikkaloukta outdoor climate to the right. "Cons" refers to a constant moisture supply while "Linj" refers to a moisture production based an all measured moisture supplies as a function of the outdoor temperature. The total energy use is Wr+Wfan.

3.7 Frosting

Figures 60-62 show results of differences between the nominal temperature efficiency and the equivalent temperature efficiency for different cases of frost prevention with different input data. The default input data is text = 22°C, balanced airflow multiplied by □ and cp and tsup = 20°C.

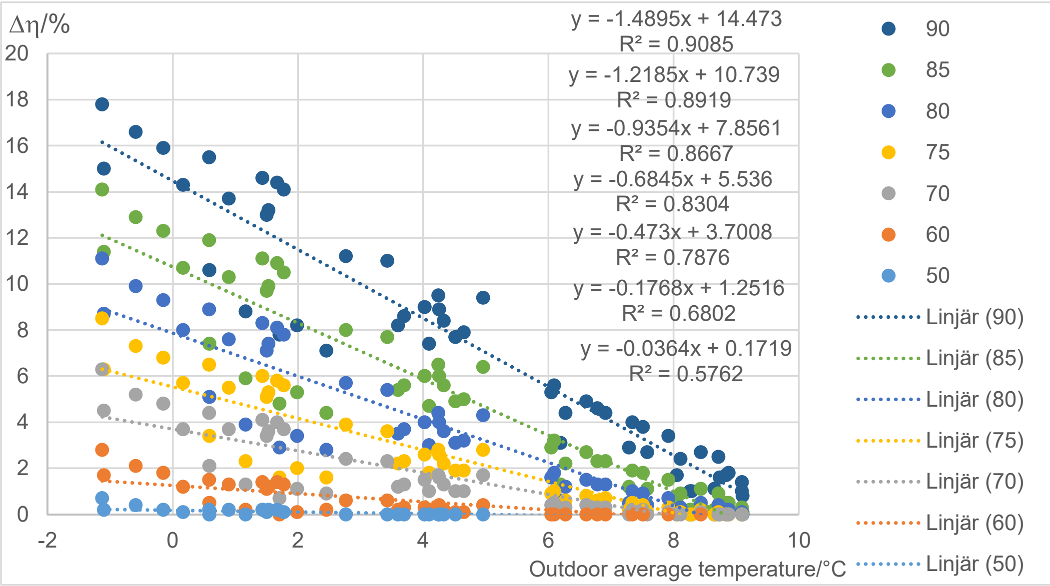

Figure 60. Correction of nominal temperature efficiency as a function of annual average outdoor temperature in the case where the exhaust temperature must exceed 0°C.

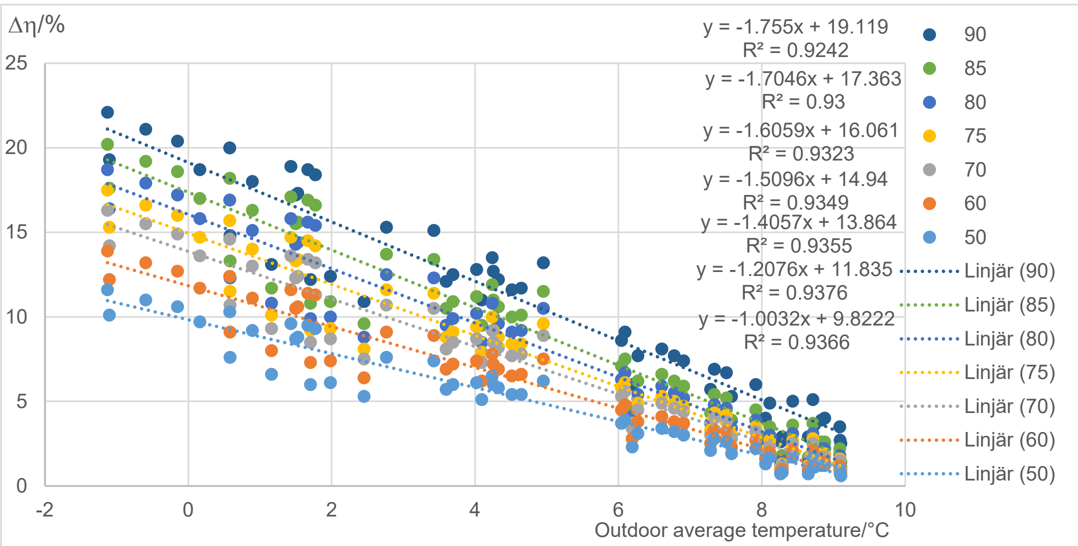

Figure 61. Correction of nominal temperature efficiency Dh as a function of annual average outdoor temperature in the case where the outdoor temperature must exceed 0°C. Linear regressions lines with complementing data are given for each nominal temperature efficiency given in the legend in descending order ("Linjär").

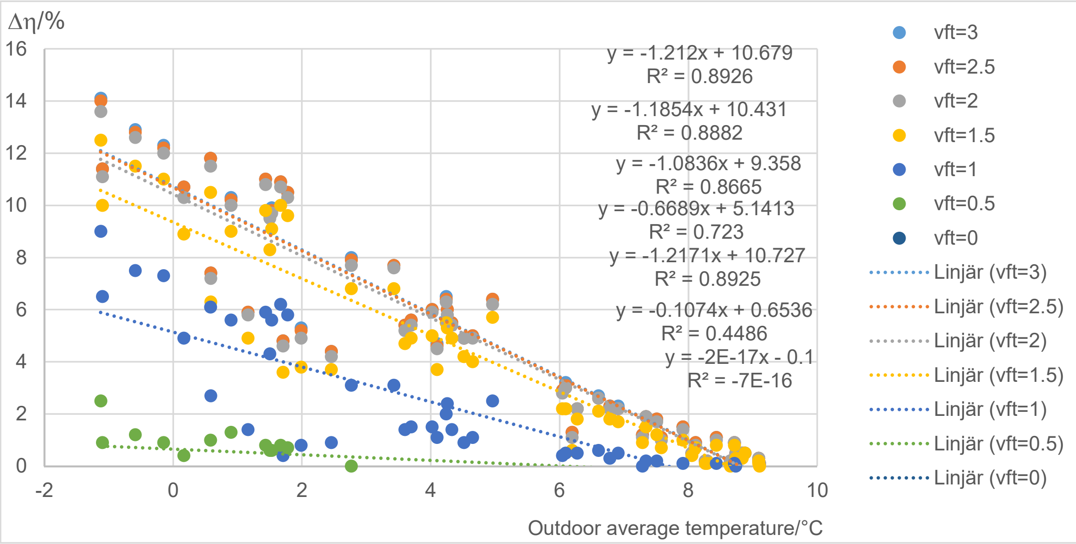

Figure 62. Correction of nominal temperature efficiency as a function of annual average outdoor temperature in the case where the exhaust temperature must exceed 0°C or must exceed the saturation temperature for different moisture supplies vft and the nominal temperature efficiency is 85%.

3.8 Tool

The Excel simulation tool can be downloaded from http://www.d-j.se/ftx.xlsm. Figure 63 shows a screen dump. It includes models and outdoor climate data and includes seven macros but the main calculations are modelled to be immediate. The macros deal with parametric runs. Every hour is represented by a row beginning with row 11 and equations are given in the cells that calculate parameters and then the result is obtained above row 11 in different fields.

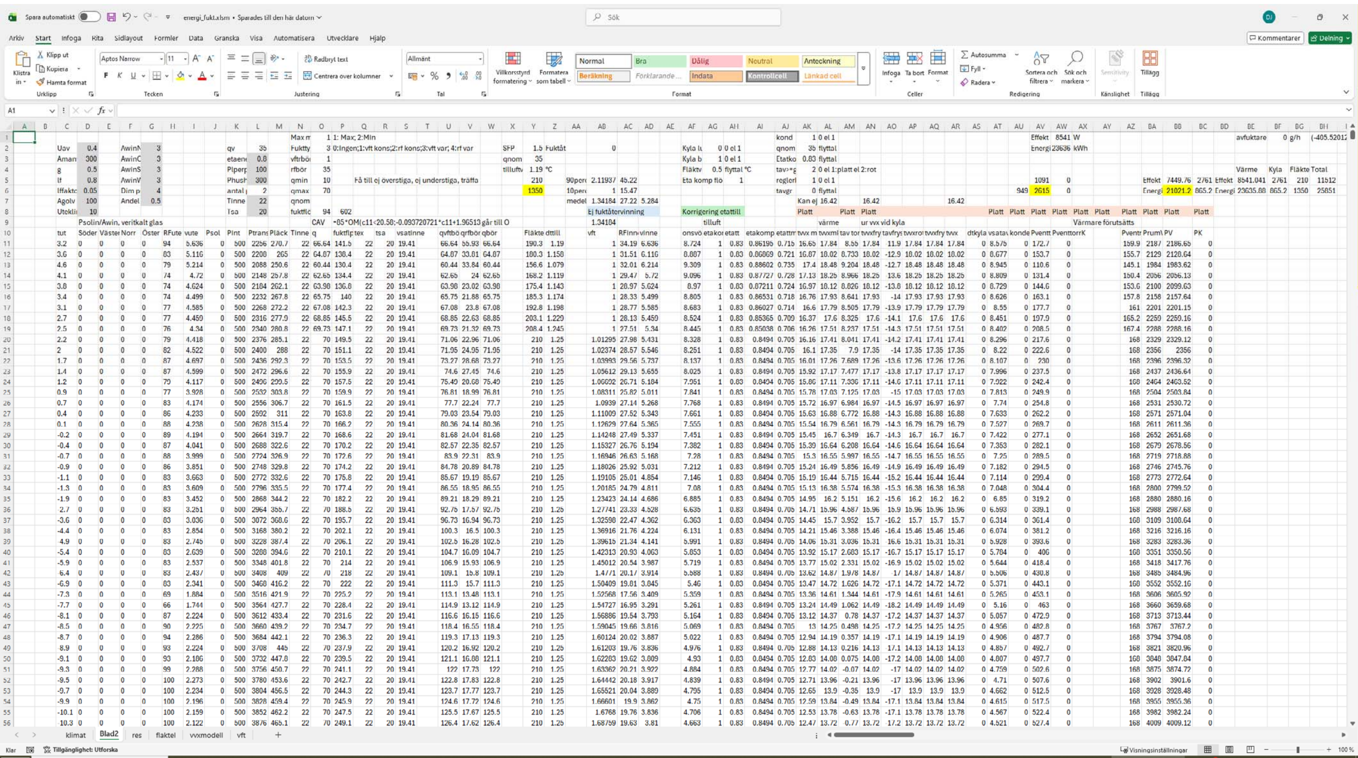

Figure 63. The Excel tool for calculations of energy use in balanced ventilations systems with heat recovery.

4. Discussion and Conclusions

Based on a lot of data on measured moisture supply and a specifically developed model for combining the building physics moisture assessment with the heat recovery system of the ventilation and its parameters, there is a tool that can be used and this report shows typical results from these simulations. Approximately 100 000 annual simulations have been done based on 602 measured dwelling years of moisture supply data, describing the actual occupational behaviour of Swedish dwellings. Apparent results are that heat recovery in ventilation systems is very beneficial from an energy perspective, even if a nominal temperature efficiency of 0 was never simulated. This is presented before, and particularly in a passive house, the heat recovery will be a large relative part of the energy use. In a decent house, like the example here, still the rest of the energy losses for heating not connected to the ventilation is a larger part.

It can be sorted out when moisture recovery of rotary wheels is beneficial to combat with increased airflow and when it is not. In cold climates, the lower risk of frosting in the heat recovery makes the rotary wheel better even with compensated flow to combat some moisture recovery. Controlling the moisture recovery is to some extent possible by the rotational speed of the rotary wheel according to the manufacturers but it is probably within limits that make it uncertain. In warmer climates with almost no frosting even in a plate heat exchanger, they may be better than the rotary wheels, but the fact that their nominal temperature efficiency cannot be controlled easily may create more cooling need and over temperatures.

Regarding the maximum power need, this may have a bigger influence in connection with power fees if the source is electricity and here is also a rather big difference when it comes to the frosting protection. When it is coldest, the maximum power is highest and then, the temperature efficiency also becomes lowest.

Moisture recovery can also be a way to increase too low relative humidity in winter time, both in colder and warmer outdoor climates. This must however be done with care to not risk the construction. Probably, even if not investigated here, demand controlled ventilation in dwellings could be a way to get a ventilation system to at least adapt to the number of people in the dwelling (Abdul Hamid et al., 2019). Now it may be possible to increase relative humidity in a dwelling where it lives one person by help of low airflow and moisture recovery and still ensure maximum moisture supply of for example 3 g/m^3 to have some margin to the commonly referred to 4 g/m^3 as design value for the building physics parameters of the construction. If then a family of 8 persons move into the same dwelling, it probably becomes much higher moisture production and the designed and adjusted ventilation system will have a problem avoiding moisture damages.

Economy has overall not been analysed in detail. An analysis in the Software Swegon System Choice gives that the cost of the ventilation system depends on the designed size of the airflow powered to 0.48 which means that the cost is not varying very much with the size if the airflow is increased moderately. The software does not give a difference between plate and rotary wheel heat exchangers and that will depend more on models, manufacturers and price negotiation than on principal costs. Demand controlled ventilation, though, is clearly more expensive and that also needs more expensive components in the duct system and, in particular, in the rooms.

Regarding over temperatures in dwellings without cooling, there is an advantage that the rotary heat exchanger can be controlled regarding the temperature efficiency. That means that a plate heat exchanger, if it has not some kind of bypass, can give warmer temperatures than desired. Sometimes it is possible to overcome by a “summer coil” that is bypassed, but this is a manual operation, and it may be too warm on days but the heat recovery is needed at nights, and in such a case, energy is wasted. A very important disadvantage not to forget with rotary wheel heat exchangers is that they transfer smell, particles etc, which to a part can be handled but it is important to have in mind.

The future research can be to really try to design a heat recovery system that handles both the problem with low RH and at the same time secure not to reach to high levels of moisture supply to risk the construction elements of the building. This must be done in practice and even if the developed model and tool cover most of it, some adjustments to the control algorithms needs to be refined. Testing such a system in a practical setup should be very interesting. There are systems on the market that control by moisture supply in dwellings but it is a challenge that it may differ in different rooms and the cost of installing such systems.

Other features that can be developed is to att a lot of measurements of different actual, practical heat exchangers and extend the analysis to more than dwellings. Cooling and the problem of heat recovery during cooling is also another problem. Applications of building buildings where it can be very interesting to adopt to a good practise for heat recovery systems is rebnovation and adaptive reuse of buildings where, by definition, the use of the building changes from one type to another, which can mean, for example, that the nice heat recovery from a rotary heat exchanger in the dry office can be a problem when the office becomes apartments instead. Another challenge is to ensure a safe humidification of buildings, by heat recovery system moisture recovery or by other means, without risk of moisture problems, mould growth or other issues.

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