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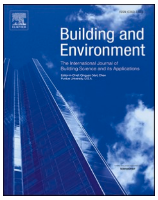

Understanding the role of moisture recovery in indoor humidity: An analytical study for a Norwegian single-family house during heating season

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ABSTRACT

Providing a high-quality indoor environment with appropriate indoor humidity levels for residential buildings is essential for good physical and mental health, occupant comfort, and long-term building performance. The role of moisture recovery in indoor humidity levels in cold climates has long been the subject of controversy; scholars have debated whether it ameliorates the problem of "too dry" air or causes a new problem of "too humid" air. The current study examines a method using moisture balance equations integrated with moisture recovery to analyse moisture recovery's effect in cold climates.

A virtual single-family house in Oslo, Norway, was used to demonstrate the impact of moisture recovery on humidity levels in the kitchen, bathroom, bedroom and living room. The results show that moisture recovery has varying influences on indoor humidity depending on the intensity of moisture recovery, moisture production and ventilation. The indoor moisture production and humidity levels were validated against large-scale field measurements in residential buildings. For the virtual single-family house, the optimal moisture recovery effectiveness is about 50–60% with a 2-min interval, as the "too dry" air (RH<20%) issue is eliminated while the risk of "too humid" air (RH>80%) is not exacerbated.

This work also identifies the possibility of controlling or optimising indoor humidity by altering the energy recovery system's moisture recovery effectiveness. Furthermore, the study's findings can be used to optimise thermal comfort or assess epidemiological risk in terms of the impact of indoor humidity.

1. Introduction

Indoor humidity is a crucial parameter for indoor air quality (IAQ), thermal comfort, occupant health, energy performance and the durability of building structures [1,2]. Sustaining indoor humidity at appropriate levels is a critical yet challenging aspect of ensuring satisfactory indoor environments [3]. Recent research has shed light on humidity's impact on viral survival, transmission and sleep quality, which affect the safe limit for indoor air humidity. Accordingly, lower and upper moisture limits are needed to be established to meet the trade-off between the requirements of indoor thermal comfort, occupant health and building structure.

In cold climates, residential buildings often suffer from low indoor humidity, which is attributed to the combined effects of low outdoor humidity levels, overheating and overventilation during the heating season [3,4]. Despite the long-standing dispute about low indoor air humidity and its associated health effects, several risk factors are linked to low indoor humidity. These include dryness of the skin and mucous membranes and sensory irritation of the eyes and upper airways [1]. Moreover, integrated analyses have shown that lower humidity increases influenza virus survival. While low humidity levels have a limited impact on thermal comfort, skin dryness, eye irritation and static electricity all increase as humidity decreases [5]. Elevating indoor humidity levels to above 30% RH may positively influence the perceived IAQ and reduce sensations of dryness during the cold period [6–8]. Moreover, recent indoor humidity measurements on approximately 1400 residential buildings in Sweden confirmed that low relative humidity is a significant problem during winter [3].

In the case of better-insulated and air-tight buildings designed to

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Nomenclature

Parameters	
G	Mass of moisture [kg]
i	Time index
m	Mass flow rate of ventilation air [kg/s]
N	Air change rate [h^{-1}]
t	Time (s)
t	Temperature [°C]
V	Room volume [m^3]
w	Humidity ratio [kg/kg]
Abbreviations	
AHU	Air handling unit
ACH	Air changes per hour
IAQ	Indoor air quality
MRE	Moisture recovery effectiveness
RH	Relative humidity
Greek letters	
η	Moisture recovery effectiveness
ρ	Density of air [kg/m^3]Subscript
amb	Ambient
ext	Extract
inf	Infiltration
m	Moisture
out	Outdoor
room	Different room index
sat	Saturated
sup	Supply
vent	Ventilation

reduce building energy use, upper relative humidity (RH) limits need to be established to maintain human comfort and diminish condensation risk on the interior surface of buildings, as well as the growth of mould and fungi inside buildings [9]. In addition, high RH and high temperature negatively affect the immediate perception of air quality (a snapshot of perception) when exposed to the emission of pollutants from building materials [10]. In one study, a four-fold increase in total volatile organic compounds (TVOCs) from the wood sample was observed as the RH in the climate chamber increased [11]. The high moisture may also deform materials, resulting in shorter building service life [3,12]. Moisture and mould damage related to building construction are commonly reported in a wide range of countries, such as Finland [13], Canada [14], New Zealand [15], Austria [16] and Norway [17].

The role of indoor humidity in the perception of IAQ, health and building structures continues to be an imperative topic in the indoor air science community. Numerous studies have been conducted over the past decades. For instance Ref. [18], recommends a range of 40–60% of RH considering the effect of RH on bacteria, viruses, fungi, and ozone production. Nevertheless, there are no widely accepted optimal conditions for RH in residential buildings to meet requirements for comfort, health and building structure maintenance. It is evident, however, that indoor humidity levels should be regulated to avoid extremes ("too low" or "too high").

Indoor air moisture is influenced by several factors, including moisture sources (e.g. human presence and activity, equipment), air change rate and airflow arrangements in rooms, moisture recovery, the release or uptake of moisture by hygroscopic surfaces of the envelope and furniture, possible condensation, and the humidity ratio of the outdoor air. Given that all the factors mentioned above are interrelated, a much-debated question is how moisture recovery affects indoor humidity levels. Some argue that a heat recovery system that includes moisture recovery can ameliorate the problem of "too dry" air, while others claim that moisture recovery increases the risk of "too humid" air. To date, relatively few studies have focused on the effects of heat and moisture recovery on indoor humidity, such as [19,20]. Svendsen and Smith [17] developed moisture balance equations for single rooms and the whole apartment where rotary heat exchangers with non-hygroscopic surfaces were used. They concluded that in dry rooms, including bedrooms and living rooms, varying indoor temperature or heat recovery could limit indoor RH levels. Furthermore, rotary heat exchangers increase room humidity, which may reduce health risks. Liu et al. [20] used machine learning to study the moisture recovery of a rotary heat exchanger, analysing moisture recovery's effect on indoor humidity. The same study showed that moisture recovery in the rotary heat exchanger could slightly increase RH in bedrooms and living rooms with low moisture production for the simulated single-family house in Oslo, Norway. Moisture recovery effectiveness is used to quantify moisture recovery intensity, which is defined as the ratio of the moisture recovery amount to the maximum moisture recovery potential. However, previously published studies are limited to low moisture recovery effectiveness with condensing non-hygroscopic rotary heat exchangers; the impact of hygroscopic rotary heat exchangers [21,22] and the emerging membrane energy exchangers [23–26] on indoor humidity have not yet been studied. Their moisture recovery efficiencies vary between 50 and 90% depending on the exchanger construction and coating or membrane materials.

The primary reason to utilise highly effective moisture recovery is to reduce the common frost problem inside heat exchangers in cold climates [24,25,27,28]. The higher the moisture recovery, the lower the risk of frosting inside the heat exchanger. Nevertheless, the recovered moisture may increase the risk of "too humid" air, which in turn leads to a higher frosting probability inside the exchangers. Hence, the optimal moisture recovery effectiveness should consider these conflicting factors.

Heat recovery in ventilation can recover 70–90% of the heat in extract air to supply air, substantially diminishing the energy demand for conditioning the outdoor air [27,29]. The use of highly efficient heat recovery is increasingly prescribed by standards and regulations. For example, the minimum temperature effectiveness required in building codes is 80% in Denmark [30], 70% in Sweden [31], 50% in Finland [32] and 80% (parameter-based requirement) in Norway [33]. Given these stricter requirements on temperature effectiveness for heat wheels in cold climates, moisture recovery may become intensive; for example, this may be the case in rotary heat exchangers, where more condensation is prone to occur [20]. In turn, moisture transfer in heat recovery is interrelated with indoor humidity, which determines indoor comfort, occupants' health, mould growth and building structure.

Moisture transfer may intentionally or unintentionally occur in heat or energy recovery systems. It can significantly reduce the energy used to condition the moist air in hot climates, such as in the case study in Hong Kong [34]. Moreover, it may diminish frost formation inside the heat recovery in cold climates [23,24]. As an additional result, the moisture recovery in heat recovery alters indoor moisture levels, as it changes the humidity ratio of the supply air in ventilation, thus changing the ventilation humidity removal capacity.

The commonly used technologies for air-to-air heat recovery applications in residential ventilation can be categorised as recuperators and regenerators according to their construction principle. Based on whether moisture transfer is present inside recuperators, recuperators can be further divided into sensible-only plate heat exchangers and total heat membrane energy exchangers. In sensible-only plate exchangers, no moisture transfers between the supply air and extract air, and the moisture recovery effectiveness is thus zero. In contrast, in membrane energy exchangers, the semi-permeable membrane enables both heat and moisture transfer between adjacent supply and extract air channels. The moisture recovery effectiveness of membrane energy exchangers can vary from 30% to 90% depending on the membrane properties and exchanger construction. As an example, a membrane energy exchanger with a maximum moisture effectiveness of 80% has been constructed and evaluated in cold climates [23].

This study does not aim to address the various moisture recovery mechanisms for different recovery technologies. Instead, it focuses on moisture recovery's effects on indoor humidity levels. The resulting quantity of moisture recovery is used as an input parameter in this study. For more information about the different heat recovery technologies and their detailed heat and moisture recovery principles, one can refer to the review on heat recovery technologies [27], the book *Total Heat Recovery* [35] and Chapter 26, "Air-to-air Energy Recovery Equipment", of the ASHRAE Handbook—HVAC Systems and Equipment [36].

To the best of the authors' knowledge, the question about the role of moisture recovery on indoor humidity remains unanswered, while optimal moisture effectiveness considering indoor environmental quality is unclear and case-dependent. The present study presents a methodology to investigate the impact of moisture recovery with an effectiveness range of 0–90%. A virtual single-family house located in Oslo, Norway is used as a case study applying the presented methods. This case study exemplifies the role of moisture recovery effectiveness and optimal moisture recovery effectiveness in achieving predefined indoor humidity targets. The main contributions and novel aspects of this work are as follows:

1. This is one of the first studies to reveal the impact of moisture recovery with a broad spectrum of effectiveness (0–90%) on indoor humidity in different rooms for different moisture production scenarios in cold climates.
2. This study provides new insights into the optimal moisture recovery effectiveness with the criterion of reducing extreme indoor RH. The results can also support the design or selection of heat and moisture recovery systems for balanced ventilation with a constant airflow rate.
3. The presented methods can be applied to specific regions, buildings and moisture production schemes to answer long-standing questions about the impact of moisture recovery on indoor humidity levels.
4. The findings represent an important contribution to the fields of moisture control ventilation, energy-efficient buildings and healthy indoor environments for cold climates.

2. Methods

In this study, moisture balance equations with ventilation systems are constructed in different rooms and air handling units (AHUs) with different moisture recovery effectiveness for the studied single-family house in Oslo. The constructed moisture balance equations are solved analytically with a 2-min time resolution. The details of moisture balance, moisture generation schemes, the studied building and the ventilation system are presented as follows.

2.1. Moisture production and movement in residential buildings

2.1.1. Moisture production

Humidity levels in a room depend on the amount of moisture produced within the space, as well as the moisture transported into and out of the space, as illustrated by Eq. (1). The number of occupants and their activities related to moisture generation determine the moisture production, $G_{sources}(t)$. The moisture transported into and out of the space is a function of mechanical ventilation, infiltration or exfiltration through the building envelope.

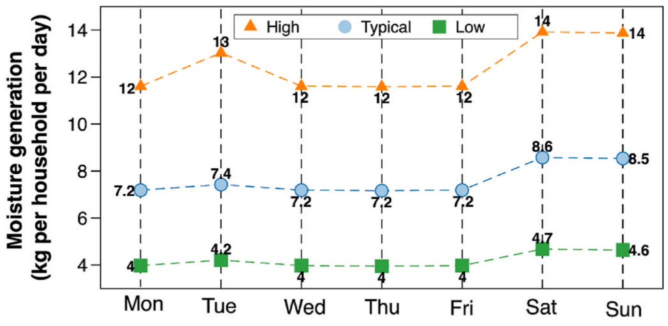

Fig. 1. Daily moisture production for low, typical and high moisture production scenarios (constructed based on [19,37,39–41]).

Table 1
Main moisture production sources and production rates formulated based on [19,37,39–41].

Sources	Room	Frequency	Units	Moisture Production [low, typical, high]
Cooking load	Kitchen	Three meals per day	kg/min	[1.6, 3.1, 3.1] (16 min for breakfast) [2.5, 2.5, 3.3] (30 min for lunch) [2.1, 2.9, 3.3] (60 min for dinner)
Cooking method	Kitchen	–	–	Electric cooker
Dishwasher load	Kitchen	Daily	kg/day	[0.05, 0.15, 0.45]
Cleaning/ mopping	All	Weekly	kg/m^2	[0.0005, 0.0005, 0.015]
Shower load	Bathroom	One shower/ occupant/day	kg/ shower	[0.20, 0.35, 0.53]
Plants	Living room	–	kg/day	[0.06, 0.20, 0.45]
Occupant (awake adult)	Living room and kitchen	–	kg/ hour/ person	[0.03, 0.06, 0.1]
Occupant (sleeping)	Bedroom	Daily	kg/ hour/ person	[0.02, 0.04, 0.1]

$$m\frac{dw}{dt} = G_{sources}(t) + G_{in}(t) - G_{out}(t) \tag{1}$$

The amount of moisture production in a single-family house, which has been documented by standards, guidelines and measurements [19, 37,38], varies substantially from 1 kg/day to 20 kg/day. To represent families' different moisture profiles, this study categorises moisture production into low, typical and high scenarios based on the values reported by various sources [19,37,39–41]. Fig. 1 shows the total moisture production per day in a single-family house with four adults for these three moisture production schemes. The figure shows that, in general, moisture production at weekends is higher than on weekdays, as it is assumed that the occupants spend more time in their houses during weekends. The moisture production for each weekday is identical except for Tuesday, when weekly cleaning and mopping occur. The weekly moisture production is assumed to be repeated throughout the year; no holidays are considered.

It should be noted that the typical scenario formulated in this study for a single-family house with four adults is slightly lower than the moisture production amount in other studies, such as [38] (e.g. approximately 10 kg/day). For Norwegian families, it is assumed that some of their habits and activities generate less moisture, such as using

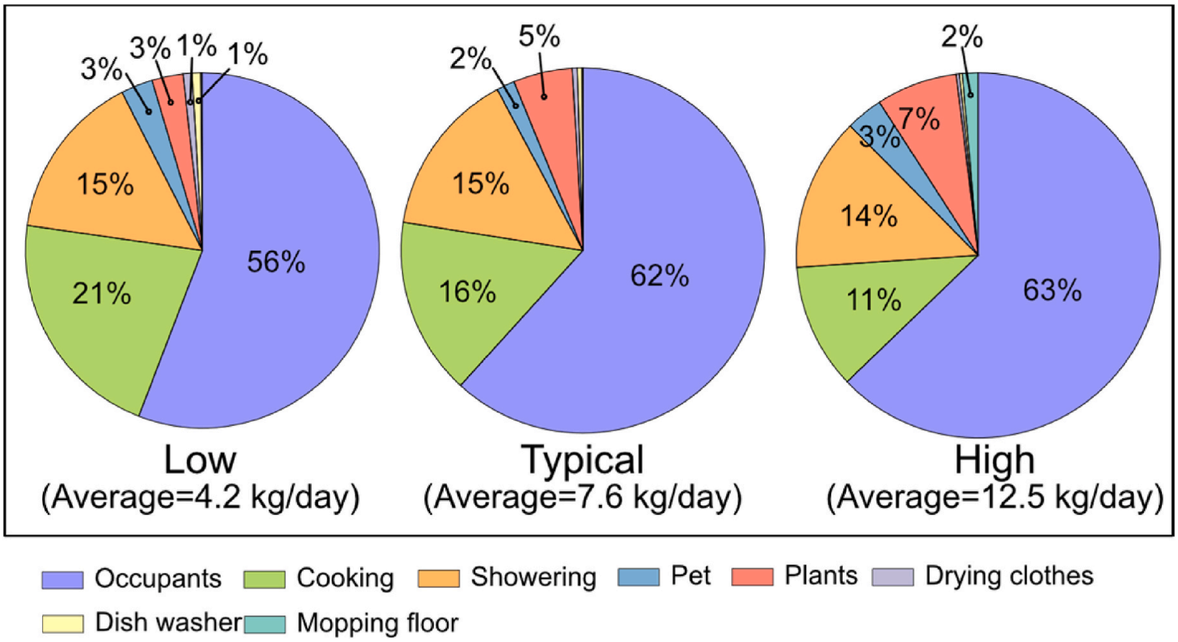

Fig. 2. Daily average moisture production and contributions from the various sources in Table 1 (based on [19,37,39–41]).

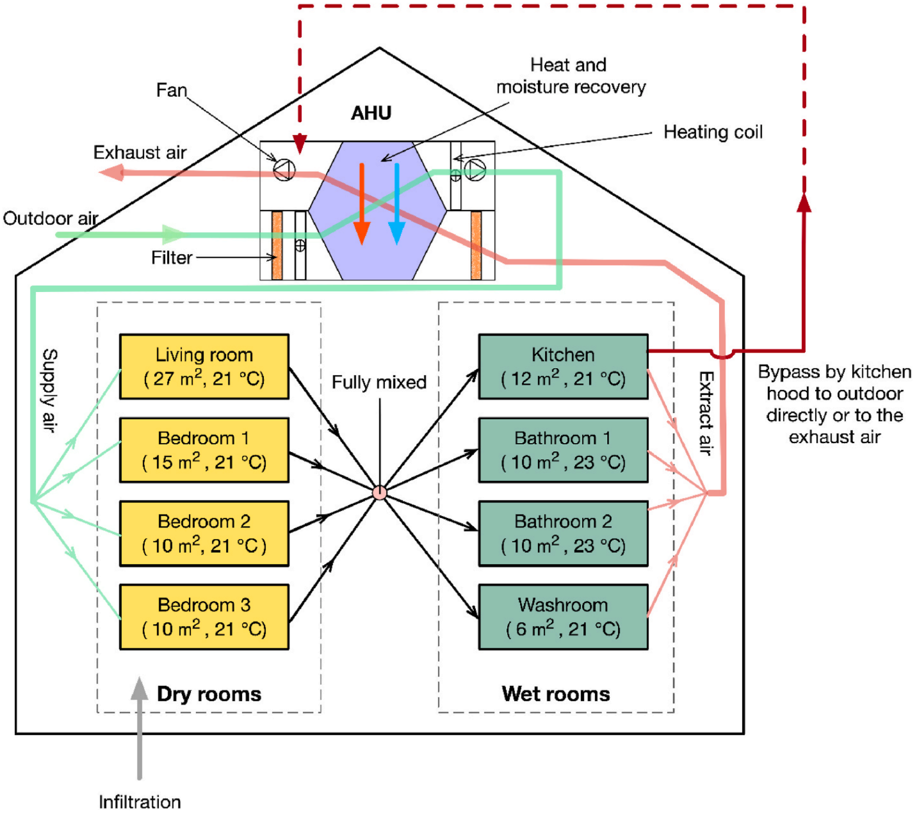

Fig. 3. An illustration of ventilation air flows and moisture movement.

electric cookers rather than gas cookers and using tumble driers instead of hanging clothes indoors. Table 1 and Fig. 2 detail the moisture generation schemes used to obtain the total daily moisture production.

Table 1 shows occupants' moisture generation location, frequency and intensity, as well as the main activities related to moisture production for the scenarios defined in this study. The moisture production from different moisture generation sources and activities has been collected from various references and adapted to Norwegian family habits and culture. These moisture production schemes and rates should be applicable to similar Nordic countries. However, this work does not consider moisture production from a sauna, which may be common in some cold climates like Finland.

Fig. 2 illustrates the daily average values for the low (4.2 kg/day), typical (7.6 kg/day) and high (12.5 kg/day) moisture production scenarios, as well as the contributions from different generation sources and activities. The moisture generated by occupants' perspiration and exhalation dominates in all three scenarios. Moisture from cooking and showering also accounts for a significant fraction of the total moisture production. About 10% of the total moisture production is generated by the remaining activities and sources.

2.1.2. Moisture movement and moisture balance equations

A dwelling's moisture distribution is predominantly driven by ventilation. Fig. 3 depicts the ventilation airflow and moisture movement of the studied house. The supply air with associated moisture is first delivered to the living room and bedrooms. These are defined as "dry rooms" with low moisture production in this study, where moisture generated from dry rooms is assumed to be perfectly mixed with supply air. Before entering the kitchen and bathrooms, ventilation air and moisture in the air are assumed to have been fully mixed. The moisture produced in these "wet rooms" is further added to the air and then extracted to the extract air, which is connected to the AHU. The moisture may transfer from the extract air to the supply air, depending upon the driving force of moisture transfer and the characteristics of the heat recovery system. Thus, moisture recovery is influenced by indoor moisture levels and outdoor air conditions, as they determine the driving force of moisture transfer. The indoor moisture levels are, in turn, affected by moisture recovery. As a result, the moisture recovery and indoor moisture levels are coupled, and the moisture balance equations are developed to connect all the aforementioned factors. The moisture transport through the building envelope by diffusion can be neglected compared to the total amount of moisture transferred by air movement [38]. In addition, the building fabric, furniture and other indoor hygroscopic materials (e.g. books) may produce a buffering effect on indoor moisture levels, depending on the building surface materials and the indoor hygroscopic characteristics. This buffering effect is not considered in this study.

The remainder of this subsection provides the essential equations used to construct the moisture balances for different rooms and nodes. The moisture balance equations are mainly derived according to Ref. [19], with complementary information as in Ref. [26].

In dry rooms shown in Fig. 3, the following iteration is derived to calculate the room air's humidity ratio.

$$w_{dry,room,i+1} = w_{dry,room,i} + \frac{G_{room,i}}{(\rho V)_{room}} - N_{inf,room}\left[min\left(w_{sat,room}, w_{room,i}\right) - w_{amb,i}\right] - N_{vent,room}\left[min\left(w_{sat,room}, w_{room,i}\right) - w_{sup,room,i}\right] \tag{2}$$

The humidity ratio of supply air ($w_{sup,room,i}$) in Eq. (2) is determined by the sum of the outdoor air humidity ratio and the recovered moisture from the extract air to the supply side. In the absence of moisture recovery – which means $\eta_{m,i}(w_{ext,i} - w_{amb,i}) = 0$ in Eq. (3) – the supply air's humidity ratio becomes the outdoor air's humidity, as residential AHUs are not typically equipped with humidifiers or dehumidifiers. In addition, supply air should have a maximum humidity ratio that is lower than that of saturated air. Eq. (3) shows the relationship between moisture recovery effectiveness, indoor moisture levels and the supply air's humidity, as described above.

$$w_{sup,room,i} = min\left\{\left[w_{amb,i} + \eta_{m,i}\left(w_{ext,i} - w_{amb,i}\right)\right], w_{sup,sat}\right\} \tag{3}$$

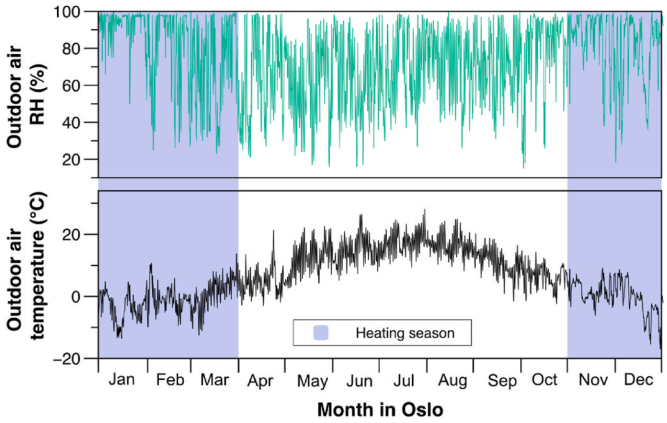

Fig. 4. Hourly outdoor air temperature and RH for Oslo, Norway during the design reference year (the blue shaded part represents the heating season used in this study, including January, February, March, November and December). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The humidity ratio of extract air, $w_{ext,i}$ in Eq. (3), is a mixture of the extract air from all the wet rooms. It can be calculated using the air-volume-weighted method:

$$w_{ext,i} = \frac{\sum\left(V_{wet,room} w_{wet,room,i}\right)}{\sum V_{wet,room}} \tag{4}$$

The moisture recovery effectiveness of the heat recovery system for balanced residential ventilation is defined as follows:

$$\eta_m = \frac{w_{sup} - w_{out}}{w_{ext} - w_{out}} \tag{5}$$

The wet rooms, including the kitchen and bathrooms, are supplied with mixed air from the dry rooms. The humidity ratio of the mixed air from all the dry rooms can be obtained with an air-volume-weighted approach:

$$w_{dry,mixed,i} = \frac{\sum\left(V_{dry,room} w_{dry,room,i}\right)}{\sum V_{dry,room}} \tag{6}$$

In the wet rooms illustrated in Fig. 3, humidity ratios are calculated in a similar way as in dry rooms:

$$w_{wet,room,i+1} = w_{wet,room,i} + \frac{G_{room,i}}{(\rho V)_{room}} - N_{inf,room}\left[min\left(w_{sat,room}, w_{room,i}\right) - w_{amb,i}\right] - N_{vent,room}\left[min\left(w_{sat,room}, w_{room,i}\right) - w_{dry,mixed,i}\right] \tag{7}$$

The following formula (derived in Ref. [23]) is used to determine the RH for the respective room based on the calculated humidity ratios through Eqs. (1)–(7), along with the corresponding room air temperature.

$$\mathrm{RH}_{room,i} = \min\left\{\frac{6.462\ \exp[5419/(t_{room} + 273.15)]}{10^7} w_{room,i}, 100\%\right\} \tag{8}$$

In Eq. (8), indoor humidity ratios, $w_{room,i}$, are allowed to exceed saturation. The surplus moisture is assumed to condense onto indoor surfaces, and it is also assumed that the condensation immediately evaporates to indoor air again when possible. The maximum RH in each room is restricted to 100%, as given in Eq. (8).

Using a 2-min resolution and climate data for Oslo, the above equations (1)–(8) are solved for one reference year. The room air

Table 2
Ventilation rates in different rooms based on the TEK17 requirements [33].

Room	Ventilation rate	Room	Ventilation rate
Kitchen	36 m^3/h (ACH 1.25 h^{-1})	Bedroom 1	52 m^3/h (ACH 1.44 h^{-1})
Washroom	36 m^3/h (ACH 2.50 h^{-1})	Bedroom 2	26 m^3/h (ACH 1.08 h^{-1})
Bathroom 1	54 m^3/h (ACH 2.25 h^{-1})	Bedroom 3	26 m^3/h (ACH 1.08 h^{-1})
Bathroom 2	54 m^3/h (ACH 2.25 h^{-1})	Living room	36 m^3/h (ACH 0.55 h^{-1})

temperatures are assumed to be ideally constant in different rooms during the heating season (Fig. 3).

Several simplifications of ventilation arrangements have been adopted in this study compared to the airflows in real buildings. For instance, in many buildings, the kitchen often shares open space with the living room, and one bathroom can be directly connected to the main bedroom. The influence of such airflow arrangements is not investigated in this work.

2.2. *Building and ventilation requirements*

2.2.1. *Studied building and studied period*

A virtual single-family house with a floor area of 100 m^2 located in Oslo, Norway is used as the study case in this work. Fig. 4 shows the hourly outdoor air temperature and RH for Oslo. The studied period is limited to the heating season; this is of the most interest for cold climates, as heating and energy recovery are typically not operated during summer. The heating season (shaded period in Fig. 4) includes January, February, March, November and December. The single-family house is assumed to comply with the latest Norwegian building regulation, TEK17 [33]. The house's layout consists of one living room, three bedrooms, one kitchen, two bathrooms and one washroom (Fig. 3). It is assumed that four adults live in the house.

2.2.2. *Ventilation*

Fig. 3 shows the cascade arrangement of the balanced mechanical ventilation for the single-family house. The studied house meets the requirements of the Norwegian TEK 17 building regulation for ventilation in a residential building [33]. The extractor in the kitchen, bathroom and washroom are required to control pollution and moisture in these rooms. The prescript ventilation rates for the "wet rooms" are summarised in Table 2. The total ventilation rate for the studied single-family house is a constant of 180 m^3/h, and the air infiltration rate is 0.16 h^{-1} (40 m^3/h). Air infiltration is introduced through all the dry rooms (the living room and three bedrooms) and air infiltration rates are assumed to be proportional to the rooms' air volume. The supply and exhaust mass flow rates of air through the heat recovery unit are assumed to be equal in the model. A kitchen hood extracts excess moisture from cooking to outdoor or exhaust air in the AHU, bypassing the AHU heat recovery. The moisture extraction effectiveness for moisture from cooking is assumed to be a constant of 75% when the kitchen hood is used.

To meet the TEK17 requirement for energy effectiveness, a minimum heat recovery effectiveness of 80% is typically needed. Like most other building codes and standards, TEK17 does not require moisture recovery.

3. Results and discussion

The methods presented in Section 2.1 are applied to the studied single-family house with the specifications in Section 2.2. This section provides the results of indoor humidity levels with and without moisture recovery.

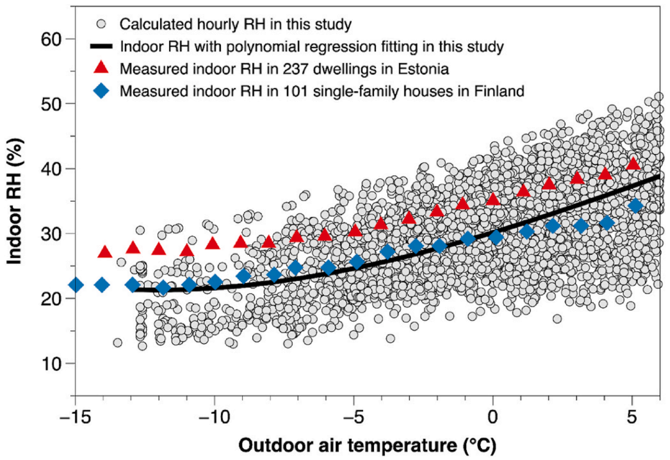

Fig. 5. Comparison between the calculated indoor RH results for typical moisture production in this study and previous measurements of indoor average RH in residential buildings in Estonia [42] and Finland [12].

3.1. *Model validation*

3.1.1. *Moisture production validation*

The average moisture production for a single-family house is modelled in the range of 4.2–12.5 kg/day in this study. Previous measurements in residential buildings in cold climates have reported average moisture production ranging from 4.0 to 11.5 kg/day [12, 42–44]. Occupants' perspiration and exhalation are the largest contributors to moisture production. This result is consistent with the findings in Refs. [19,42]. The equivalent latent heat production from a single adult for the typical scenario in this study is 30 W, which is similar to the recommended value (31 W) for a seated occupant in the ASHRAE Handbook Fundamentals [45].

3.1.2. *Indoor RH validation*

The indoor RH with no moisture recovery calculated using the proposed model are compared to large-scale indoor RH measurements for residential buildings in Estonia [42] and Finland [12]. In Finland, the indoor humidity levels of 101 lightweight timber-frame single-family houses have been measured and analysed [12]. The measured daily average temperatures during the cold period (outdoor air temperature <5 °C) of all the rooms of these 101 houses were between 21 and 22 °C, depending on the outdoor air temperature. In comparison, the volume-average room air temperature in the proposed model is 21.4 °C. The 101 Finnish houses had three ventilation systems: natural ventilation (10 houses), mechanical exhaust ventilation (29 houses) and balanced mechanical ventilation (62 houses). The moisture recovery information for these measurements is not found in Ref. [12].

In Estonia, Ilomets et al. [42] examined several years of field measurements of indoor hygrothermal conditions in 237 Estonian dwellings, including 180 apartments and 57 detached houses. Of these 237 dwellings, 51% of the apartments and 55% of the houses had natural ventilation systems, while the rest had mechanical systems. The average room air temperatures with central heating systems were in the range of 22–23 °C during the cold period (outdoor air temperature <5 °C). Information about moisture recovery in ventilation is not found in Ref. [42].

The indoor average RH values based on these measurements in Finland and Estonia are compared to the results in this study for the cold period (outdoor temperature ≤+5 °C; Fig. 5). The measurements and the results calculated in this study are not fully comparable due to differences in the ventilation system, room air temperature and missing information on moisture recovery in the measurements. Nevertheless, the

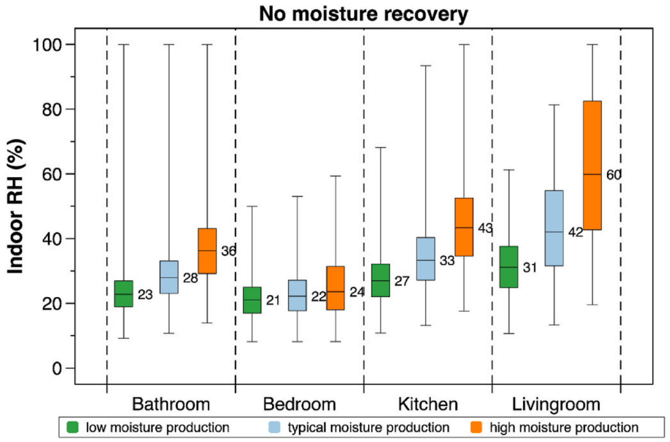

Fig. 6. Indoor air RH distribution in different rooms with no moisture recovery in AHU at a 2-min time resolution during the heating season (Boxplot explanation: the horizontal line in the middle of the box represents the median value. The horizontal lines at the bottom and top of the "box" represent the 25% and 75% percentiles, respectively. The top and bottom horizontal lines represent the maximum and minimum values. All boxplots in this work have the same denotation.).

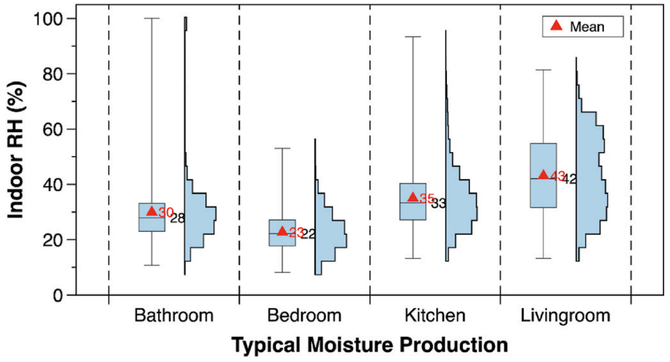

Fig. 7. RH probability distribution during the heating season for the typical moisture production scenario with no moisture recovery.

comparison is useful for examining the trend of the calculated results and evaluating the average agreement between the calculated and measured data. Despite the missing information on moisture recovery in all the measurements, the authors expect very low or no moisture recovery, as total heat recovery – which has relatively high moisture recovery – was rarely equipped in these ventilation systems based on the authors' experience. The calculated hourly indoor RH (Fig. 5, grey points) is fitted to a third-order polynomial regression-fitting model (Fig. 5, black line) with the least square method. The RH values estimated by the polynomial regression in this study are similar to the field measurements in both the Estonian and Finnish houses, but they are more consistent with the measurements in the Finnish houses. The probable explanation is the high similarity in building types and climates between the Finnish houses and this study's Norwegian setting relative to the Estonian dwellings, which include apartments as well as single- and multi-family houses.

3.2. *Indoor air relative humidity with no moisture recovery*

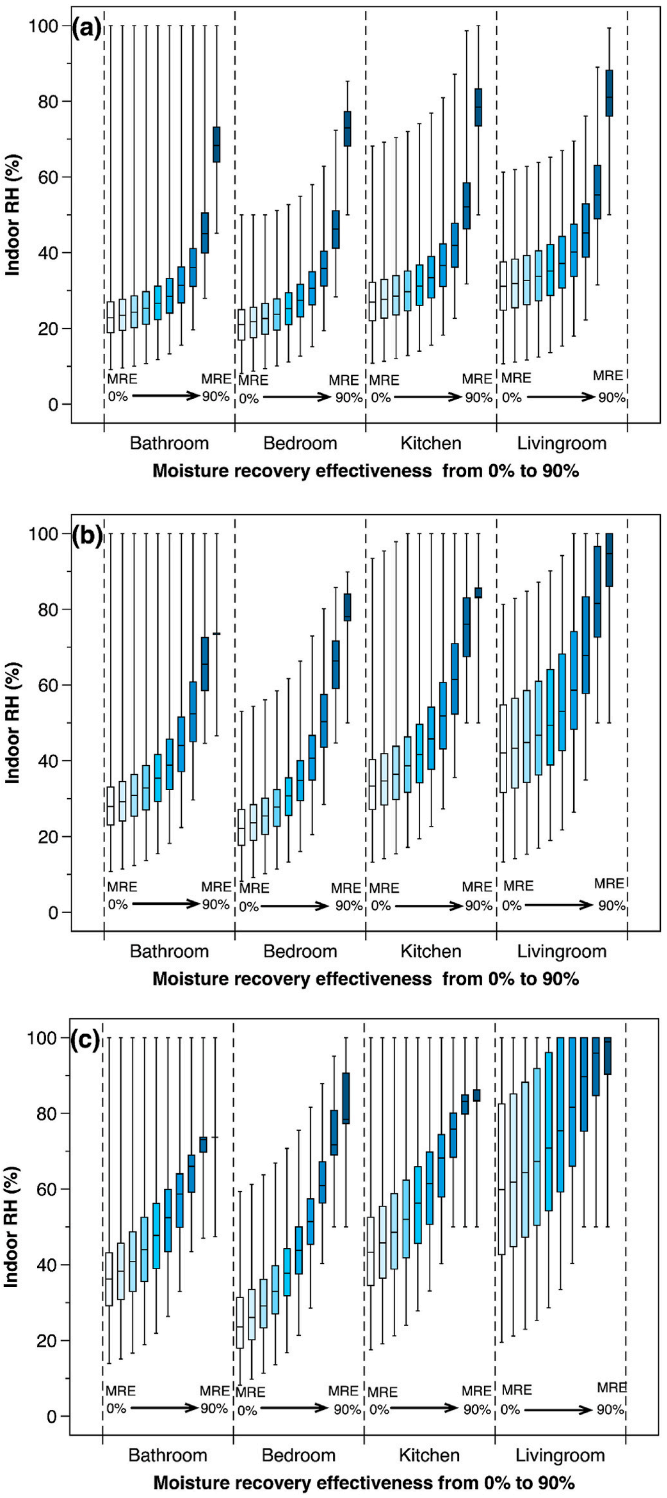

Fig. 8. Indoor RH with different moisture recovery effectiveness during the heating season for (a) low moisture production, (b) typical moisture production, and (c) high moisture production (MRE = moisture recovery effectiveness).

This subsection shows the results of indoor air RH in different rooms of the studied house with the simulation's 2-min time resolution. Only the simulation results for the heating season, which is defined as November to March for Oslo, are presented. During heating seasons, RH levels are of greatest concern. Heat recovery is more active during these seasons than during summertime and shoulder seasons, when the overheating control prevents heat recovery from being used. There are no widely agreed-upon RH limits, as indicated by the summary of RH effects and limits in Section 1. In this study, the upper and lower limits of

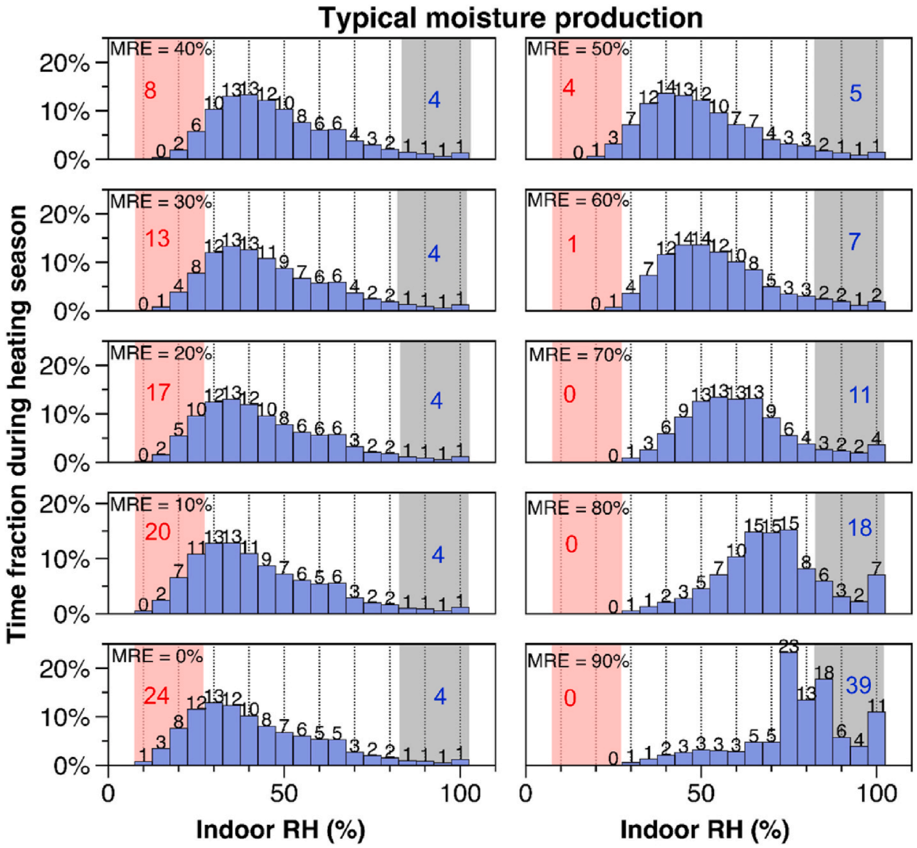

Fig. 9. Time fraction of indoor RH levels in all rooms with various moisture effectiveness values for typical moisture production during the heating season (The area shaded in red is "too dry" air with RH below 20%, and the red values are the sum of the time fraction of dry air. The area shaded in grey is "too humid" air with RH over 80%, and the blue values are the sum of the time fraction of humid air. MRE represents moisture recovery effectiveness). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

indoor air RH are 20% and 80%, respectively. The boxplot in Fig. 6 presents the indoor RH distributions with a 2-min time interval and no moisture recovery for different rooms in the three defined moisture production scenarios. The lowest RH in all rooms with low and typical moisture production is about 10%. In all moisture production scenarios, the air in the bathroom reaches saturation when occupants take a shower. In the kitchen, the air only saturates in the high moisture production scenario. Comparing the same moisture production scenario, the living room has the highest RH levels, followed by the kitchen and bathroom; this is due to the occupants' prolonged presence in the living room. The bedroom is the dryest room. It should be noted that the air temperature substantially influences indoor RH. The bedroom air temperature in this study is set at 21 °C, which is higher than the reported values in Norwegian homes [46]. This can be attributed to the definition of the moisture scheme, in which all occupants are present in the living room when they are home. In comparison with the living room, the bathroom and kitchen have higher peak loads of moisture, but the occupants spend much less time in these rooms. Fig. 6 shows that the amounts, sources and activities of moisture generation agree with Fig. 2. Overall, the humidity levels in all rooms in the low and typical moisture production scenarios are low. The results demonstrate that occupants may experience the "dry air" issue to the greatest extent when sleeping in their bedrooms during the heating season.

In Fig. 7, the boxplot results for the typical moisture generation scenario (which can be considered representative of most families) are taken from Fig. 6 and plotted together with a more detailed probability distribution on the right side of the boxplot. In the typical moisture production scenario, the indoor RH levels of the bathroom, bedroom, kitchen and living room are lower than 32%, 28%, 40% and 52%, respectively, for 75% of the time during the heating season. Compared with the other rooms, the RH fluctuations in the living room are higher, reflecting the presence or absence of occupants and their high moisture production in the living room. Bathrooms have a very low probability of having RH levels between 50% and 90%. Note that the moisture transfer in this study simplifies the mixing of moisture and air temperatures before transfer from room to room; in reality, air flows and air mixing might might exhibit different patterns.

3.3. *Effects of moisture recovery on indoor humidity*

In this subsection, the effects of moisture recovery on indoor moisture levels are analysed using the methods described in Section 2. Fig. 8 shows the trends of indoor RH distributions when the moisture recovery effectiveness increases from 0% to 90% in different rooms with low, typical and high moisture production. In all cases, the indoor RH levels are raised by increasing the moisture recovery effectiveness. Fig. 8 shows that the indoor RH levels sharply rise when the moisture effectiveness reaches 80% or 90%, especially in the low moisture production scenario. This is because ventilation's moisture removal function is very limited when moisture effectiveness reaches 80% or 90% with a constant ventilation rate and room air temperature. Furthermore, the simulation does not include the effects of opening exterior doors and windows, which enhances moisture dilution.

On the one hand, the dry air issue can be improved in the bedrooms with moisture recovery for different moisture production scenarios. On the other hand, high moisture recovery may risk "too humid" air in the living room, which has the highest moisture production.

In the heat recovery system, moisture recovery can reduce or even eliminate the frosting problem, which leads to low energy recovery and blockage of the heat exchanger in cold climates. It has been found that higher moisture recovery effectiveness corresponds to lower frosting risk in the heat exchanger and, correspondingly, greater energy savings for the ventilation system [26]. Nevertheless, the indoor RH results from Fig. 8 demonstrate that high moisture recovery effectiveness can result

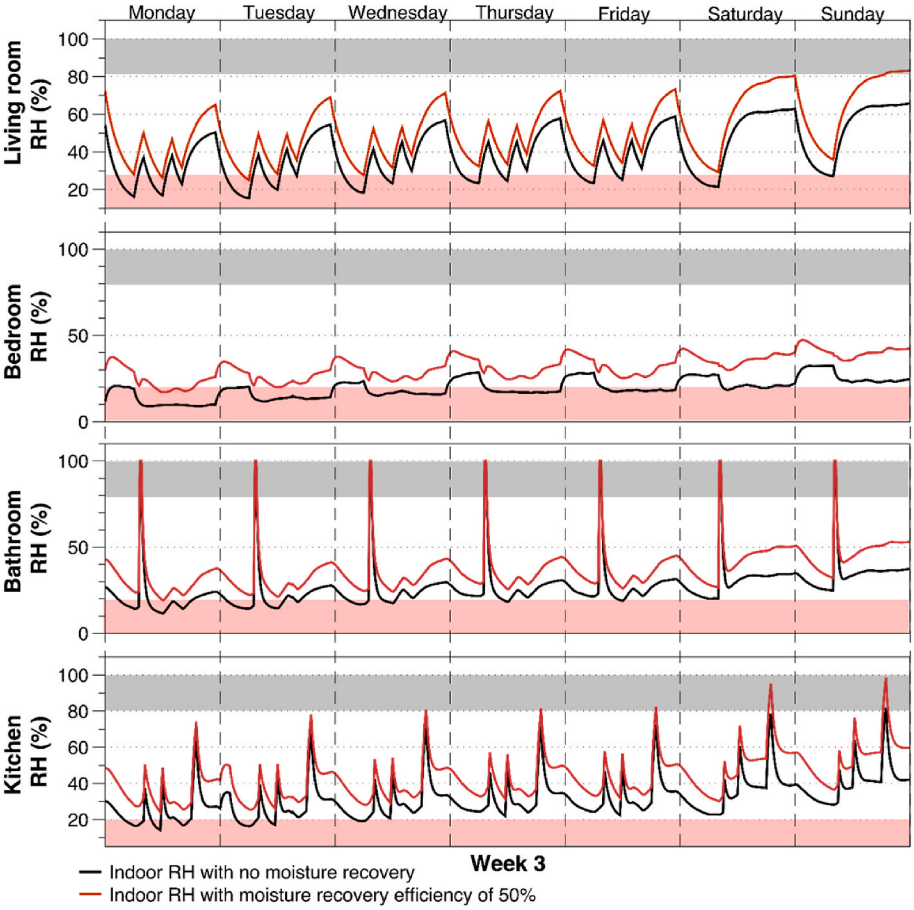

Fig. 10. Indoor RH profiles in different rooms with a typical moisture production scenario for week 3 (The area shaded in red is the "too dry" air with RH below 20%. The area shaded in grey is the "too humid" air with RH over 80%). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in "too humid" air even with a low moisture production rate. Given these findings, optimal moisture recovery effectiveness should comprehensively consider the indoor environment, frosting risk inside the heat exchanger and energy savings through heat recovery. The heat recovery design and selection criteria could be further established based on the effectiveness of heat and moisture recovery.

To better understand the selection of moisture recovery effectiveness considering its effects on indoor moisture levels, Fig. 9 shows the time fraction distributions of RH with different moisture recovery efficiencies in the typical moisture production scenario for the whole house (all the rooms).

Through this analysis, one can define an optimal RH range or ranges to avoid. Using the data presented in Fig. 9, the total time fraction within or outside the optimal range can be determined for different levels of moisture recovery effectiveness. As an example demonstrating how the results can be utilised, this study chooses the "too dry" (RH lower than 20%) and "too humid" ranges (RH higher than 80%) for the cold period. As can be seen in Fig. 9, the sum of the time fraction for "too dry" air – the red shaded area and red values in Fig. 9 – is reduced from 24% to 0% with increased moisture recovery effectiveness. In other words, the "too dry" air (lower than 20%) can be eliminated with the support of moisture recovery. At the same time, the "too humid" air becomes more frequent with increasing moisture effectiveness. The time fraction of RH over 80% does not increase until the moisture recovery effectiveness reaches 50%. For moisture recovery effectiveness in the range of 70%–90%, the "too humid" air (RH over 80%) rises steeply from 11% to 39%, as shown in the blue values and the shaded grey areas. As concluded before, high moisture recovery effectiveness should be avoided considering the potentially problematic indoor moisture. In this case, moisture recovery effectiveness of around 50–60% yields the optimal outcome, as the dry indoor air is significantly improved and the high indoor moisture risk does not increase too much.

It should be noted that this study does not aim to specify humidity limits. The 20% and 80% RH values were chosen to demonstrate how the developed method can be utilised to support the determination of optimal moisture recovery efficiency given indoor limits. Therefore, this paper’s findings concerning optimal moisture recovery efficiency cannot be extrapolated to other scenarios with different indoor humidity limits. In addition, the calculation time interval is 2 min in this study. The time interval of indoor RH could be changed to larger time intervals as necessary by averaging the 2-min data (using a method such as moving average). The indoor RH data with a 2-min time resolution for different rooms during the heating season is available on request.

The above case study exemplifies how the results in Fig. 9 can be used to determine the optimal moisture recovery effectiveness based on indoor RH levels. As previously stated, one can choose optimal RH ranges based on the relevant requirements. These results can also be applied in other ways, such as optimising thermal comfort with the PMV method or assessing epidemiological risk using indoor moisture profiles. For the sake of conciseness, Fig. 9 only presents the typical moisture production scenario. The low and high moisture production scenarios can be found in Figures A.1 and A.2 in the Appendix.

Fig. 10 shows the moisture profiles in different rooms for week 3 with no moisture recovery and with a moisture recovery effectiveness of 50%. The RH ranges for "too dry" air and "too humid" air are shaded with the same colours as in Fig. 9. Fig. 10 shows that a moisture recovery effectiveness of 50% can lift the "too dry" air in the living room – and especially the bedrooms – to more optimal RH values in week 3. While this moisture recovery increases the probability of "too humid" air in the kitchen and living room, this elevated risk occurs for a relatively short period and only during weekends, when the indoor moisture loads are higher due to the prolonged presence of occupants and longer cooking times. It is possible to solve the issue of excessive moisture in kitchens by increasing the forcing ventilation rates of the kitchen hood, thereby bypassing the heat exchanger in AHU during cooking. In conclusion, indoor RH levels can be controlled and improved by regulating moisture recovery effectiveness.

3.4. Limitations of this study and future work

This study presents a methodology to explore the impact of moisture recovery on indoor humidity levels, thereby supporting the design of heat or energy recovery devices. Only one single-family case in Oso, Norway, with fixed room air temperature, ventilation rate, and perfect mixing ventilation, was studied. More scenarios with different settings for different climates are suggested for future study. The moisture buffering effect from building interior surfaces, furniture and other moisture adsorption stuff like books are not considered due to the uncertainties of surface temperature, building materials and the complexity of modelling moisture buffering. Neglecting the moisture buffering effect may enlarge the calculated indoor moisture fluctuations to some extent. The measurements used for validation in this study are not fully harmonised with the model settings as difference exists in room air temperature, ventilation systems, building archetypes and missing information on moisture recovery in measurements. New measurements with and without moisture recovery effectiveness in real buildings with recorded moisture generation will be valuable to provide better comparability in validation and tested evidence on the impact of moisture recovery.

4. Conclusions

This study set out to analyse the impact of moisture recovery on indoor humidity levels. Moisture balance equations incorporating a moisture recovery function were used to calculate the indoor humidity levels in the kitchen, bathroom, bedroom and living room in low, typical and high moisture production scenarios. This work used a virtual single-family house with four adult occupants as a case study, and the indoor moisture production and RH levels were validated against previous field measurements in residential buildings. The main conclusions are summarised below:

1. For the first time, the impact of moisture recovery with effectiveness from 0% to 90% on different rooms in a single-family house was evaluated. The moisture recovery can significantly influence indoor humidity depending on the moisture recovery effectiveness and indoor moisture loads.
2. The optimal level of moisture recovery effectiveness can be determined by assessing the time fraction of RH levels within the defined optimal RH ranges to yield a satisfactory and healthy indoor environment. For the defined RH ranges and the studied single-family house with typical moisture production, the optimal effectiveness has been identified as 50–60%; at this level, the problematic "too dry" air is eliminated and the "too humid" air issue is not exacerbated by moisture recovery.
3. This study identifies the possibility of using moisture recovery in AHU to control or optimise indoor humidity levels. This study addresses the long-standing dispute about whether moisture recovery in cold climates may improve the frequent issue of "too dry" air in winter; some have argued that moisture recovery can increase the risk of "too humid" air. With the method presented in this study, the dispute can be addressed for specific climates, dwellings and moisture generation schemes.
4. The results of this work can also be extended to thermal comfort optimisation and epidemiological assessment. Together with frosting limits for heat recovery systems and energy savings, this study can inform criteria for designing or selecting heat recovery systems.

CRediT authorship contribution statement

Peng Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Justo Alonso:** Writing – review & editing, Software, Methodology, Formal analysis. **Hans Martin Mathisen:** Writing – review & editing, Resources, Project administration, Methodology. **Anneli Halfvardsson:** Writing – review & editing, Methodology. **Carey Simonson:** Writing – review & editing, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

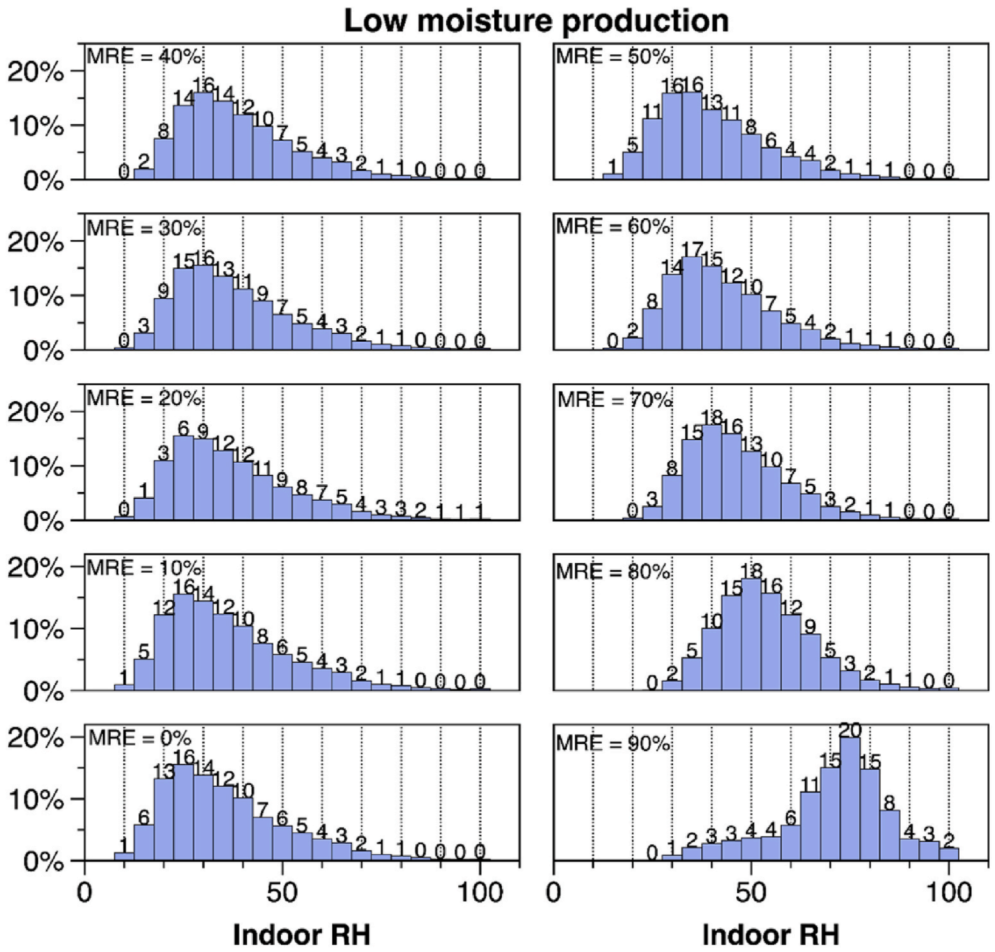

Fig. A.1. Time fraction of different indoor RH with various levels of moisture recovery effectiveness for low moisture production.

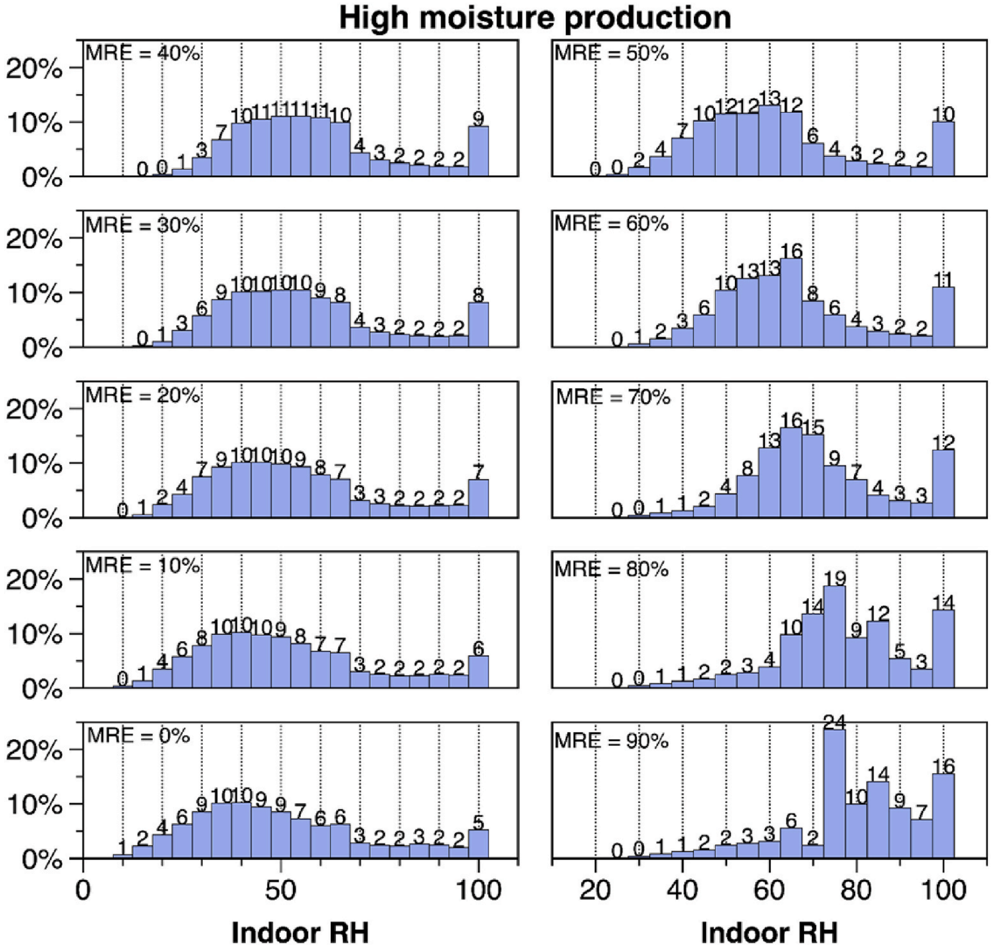

Fig. A.2. Time fraction of different indoor RH with various levels of moisture recovery effectiveness for high moisture production.

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