Field test of dehumidifiers for avoiding condensation in unheated historical wooden houses

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Abstract. The UNESCO world heritage "Decorated Farmhouses of Hälsingland" represent a well-preserved Swedish regional timber building tradition from the 18th and 19th centuries, featuring wall paintings of high cultural and artistic value. The houses have remained unheated and naturally ventilated over centuries, and have relatively leaky building envelopes. Recent indoor climate measurements and observations, however, have identified occasional condensation on indoor surfaces during unfavourable weather changes in wintertime. Such condensation poses a risk of degrading the wall paintings and other valuable objects, although low winter temperatures prevent mold growth. To mitigate condensation risk, sorption dehumidifiers – working also at temperatures below 0 °C – were installed in one of the UNESCO farmhouses during a winter season. The dehumidifiers were programmed to limit the indoor air relative humidity (RH) at maximum 80 %, and their dried air was distributed to all rooms via a flexible ductwork. Additionally, climate loggers and passive tracer gas technique were employed to measure temperature, RH, and air change rate in all rooms. By comparing with measured indoor climate in other similar farmhouses in the region, the results indicate that the dehumidifiers chiefly managed to limit RH at 80 %, thus preventing condensation in all rooms, despite a relatively high mean air change rate of around 0.8 ACH. However, locally and temporarily, enhanced RH peaks occurred, possibly due to unfavourable transient wind and/or stack conditions. The study also provides some practical installation guidance.

1 Introduction

In 2012, seven farms in the Swedish region Hälsingland, representing around 1000 similar farms, were inscribed on UNESCO's World Heritage List under the name "Decorated Farmhouses of Hälsingland." The main attractions of these heritage sites consist of large wooden, prestigious festivity buildings from the 18th and 19th centuries, including beautifully painted indoor wall hangings, wallpapers, and furnishings. Historically, these buildings were used only rarely at very important celebrations, such as marriages; otherwise, they were practically always left unused and unheated. Thus, they have been well preserved to posterity. One of the seven heritage buildings, Erik-Anders, erected in the 1820s, includes several cultural and aesthetic interiors and paintings from around 1850-1950. The festivities hall on the upper floor has surface layers of fabric with original paintings by the Knutes, a famous painting family from Dalarna. The building stands on a crawlspace of granite rocks, situated on a slope. The timber frame is visible on the entrance side (see Fig. 1), while the other facades are covered with vertical panelling. The farm is located rurally, 6 km southwest of Söderhamn, approximately 15 km from the Baltic Sea (coordinates 61°16'20.8" North, 16°59'35.6" East).

Fig. 1. World Heritage Erik-Anders farm house.

The University of Gävle's (HiG) analysis of weather data during critical periods in December 2021 revealed temporary indoor relative humidity levels of up to 100%, coinciding with rapid weather changes from long term cold to warm, possibly with rain/snow mixed precipitation and high outdoor relative humidity. Such weather shifts are likely to cause high indoor humidity levels, including condensation, due to lingering cold in building materials while relatively humid and warm outdoor air infiltrates the building. Supplementary climate data from other monitored farms suggest that

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this phenomenon may occur sporadically each winter, often accompanied by freezing temperatures, increasing the risk of deterioration of decorations and materials. Fig. 2 displays an old miscoloring (due to water leakage) of a wall painting, which seems to have become more pronounced due to condensation/high humidity.

Fig. 2. Festivities room in Erik-Anders Farm, showing significant moisture «blooms» on the southwest exterior wall.

HiG, commissioned by the County Administrative Board of Gävleborg, conducts long-term measurements of humidity and temperature in six unheated farmhouses, five of which are part of the World Heritage. Initial measurements in 2014-2015 indicated significantly high moisture levels in the crawlspaces, posing a risk for mold growth. Subsequently, the focus has mainly been on these spaces. However, the owner of the heritage site Erik-Anders observed clear signs of very high indoor humidity in December 2021, leading to concerns about potential damage to painted surfaces and decorations. These observations were confirmed by a conservator (who happened to be at the site during that occasion), who suspects that such humidity episodes contribute to increased problems with old painted wallpapers detaching and other related deterioration issues.

To mitigate extremely high indoor humidity during winter, HiG experimented with temporary installation of sorption dehumidifiers inside the Erik-Anders building during the winter of 2022-2023. Importantly, such installations must be mobile in terms of being mounted prior to the winter season and demounted in spring before the tourist season starts. This paper presents results of these trials and discusses installation issues and suitable future tests.

2 Materials and methods

2.1 Selection of dehumidification technology

In collaboration between the property owner, the County Administrative Board of Gävleborg, and the University of Gävle, three dehumidification strategies were considered:

1. Protective heating: Increasing indoor temperature raises the saturation vapor content of the indoor air and reduces condensation risk by elevating both air and surface temperatures, for example, using mobile electric radiators.
2. Condensating dehumidification: Cooling indoor air in an apparatus causes condensation of air vapor, the condensate is collected in a container or drained out of the building. This apparatus requires electricity for operation.
3. Sorption dehumidification: Removing moisture from indoor air using an apparatus that uses a warm air stream and a desiccant material for dehumidification. It also works below 0 °C. Requires electricity for operation, as well as ducting for ventilation air through the building envelope.

Alternative 1 was deemed a long-term expensive option for the property owner, despite the low purchasing cost of electric radiators; see further concerns in the Discussion section. Alternative 2 has attractive operating costs but poses challenges in an unheated building, complicating the handling of condensate due to winter freezing risks. This requires repeated manual management of collected water and/or electric heating (heating cables) for drainage pipes. Alternative 3 was attractive in terms of electricity use because dehumidification within the unit occurs through heat recovery in a rotor that simultaneously dehumidifies indoor air and rejects moisture with air. In the decision-making process for a system with lower operating costs (alternatives 2 and 3), contact was made with companies marketing such systems and researchers who have tested such systems within the Swedish Energy Agency's "Save and Preserve" program, which coordinates research on energy efficiency in culturally significant buildings (https://sparaochbevara.se/). Sorption dehumidification (alternative 3) was chosen, given the risk of condensate freezing with alternative 2.

The sorption dehumidifiers used in the study (one per floor) were manufactured by Seibu Giken DST AB, Spånga, Sweden, model DST DR-30D with a hygrostat and regulator EH3 T2. In addition to the latter control system, the unit comprises four basic components, as shown in Fig. 3.

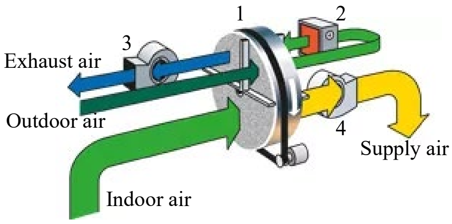

Fig. 3. Schematic of the dehumidifier unit (based on figure from Seibu Giken DST AB) which includes a heat and moisture-exchanging rotor (1), an electric heater (2), an exhaust fan (3), and a circulation fan (4).

The rotor (1) passes three chambers that are traversed by air in different conditions, interacting with and altering their states. The rotor has channels through which air can flow. It is made of metal, coated with silica gel, which has unique properties to adsorb and release moisture depending on the air's humidity and temperature. When indoor air is drawn in by the circulation fan (4) in the lower part of the rotor, this air is dehumidified as it passes through (silica gel adsorbs moisture) and is blown out as dry supply air. Simultaneously, in the upper half of the rotor, there is an air stream that passes through the rotor in two directions. Outdoor air is drawn in by the exhaust fan (3) where preheating occurs (and possible dehumidification of the rotor). This air is further heated in the heater (2) and then passes through the upper left part. While passing through the rotor, moisture bound onto the silica gel receives heat to evaporate, and finally the warm exhaust air carrying the moisture is rejected to the outdoors. It is important that the duct blowing out the exhaust air is thermally insulated and not too long as to avoid condensation.

2.2 Sizing of the dehumidifiers

The air infiltration rate into the building is crucial when condensation occurs due to quick weather changes. The air change rate in Erik-Anders building was initially unknown. However, two previous studies were conducted using tracer gas technique [1], where wintertime air exchange was measured in the World Heritage farms Gästgivars and Kristofers, corresponding to approximately 0.6 air changes per hour (ACH) and 1.0 ACH, respectively [2]. The latter value was used in the initial assessment of the dehumidification need. Measurement of the actual value in the Erik-Anders building was conducted during the test period (yielding 0.76 ACH – see under Results).

Design calculation guidelines were provided by the supplier. These were based on daily mean values for Söderhamn for a typical year, utilizing climate data from Copernicus Climate Change Service with input from 1991 to 2020 (Data sources - Climate-Data.org), i.e. typical meteorological climate. The calculations set a preliminary baseline for maximum indoor relative humidity at 73% and air exchange at 1.0 ACH as shown in Table 1.

Table 1. Basis for calculation of dehumidifier size and power consumption. ΔX [g/kg] refers to the amount of moisture that must be removed per kg of indoor air. Other energy data are linked to the unit model. Volume refers to the approximate volume of the entire building, later adjusted to 500 m³.

	Daily mean temp and RH Ref. Climate-data.org Söderhamn			Desired indoor condition			ΔX	Moisture load amb. air	Dehumidifier Capactiy	Dehumidifier Power/unit inkl fläkt	Dehumidifier Spec. el. consumption	Electricity consumption
	°C	% RH	X g/kg	°C	% RH	X g/kg	g/kg	kg/h	kg/h/unit	kW	kWh/kg	kWh
Oct	6,3	82	4,84	6,3	73	4,31	0,54	0,42	0,96	1,5	1,56	302
Nov	2,2	85	3,76	2,2	73	3,22	0,53	0,42	0,85	1,5	1,76	537
Dec	-1,2	82	2,83	-1,2	73	2,52	0,31	0,25	0,74	1,5	2,03	372
Jan	-3,2	83	2,47	-3,2	73	2,17	0,30	0,24	0,67	1,5	2,24	393
Feb	-2,9	81	2,46	-2,9	73	2,22	0,24	0,19	0,69	1,5	2,17	282
Mar	-0,3	77	2,84	-0,3	73	2,69	0,15	0,12	0,76	1,5	1,97	172
Apr	4,5	71	3,69	4,5	73	3,80	-0,10	-0,08	0,9	1,5	1,67	
											Total:	**2059**
	Air leakage	AC/h		100 %								
	Calculated volume			660 m³								

In Table 1, the moisture load (i.e., the amount of moisture that needs to be removed on average, measured in kg/h) is outlined. The capacity refers to the dehumidification capacity of a unit, influenced by the prevailing climate (both temperature and relative humidity affect it). The nominal capacity for the dehumidifier in Table 1 was 1.1 kg/h (though this is not the maximum capacity; note that the capacity declines at lower temperatures). Two such dehumidifiers, one for each floor, were chosen. Each could be controlled based on a sensor for air relative humidity, "air-RH," or alternatively, an air-RH sensor in combination with a surface temperature sensor. The RH sensor was placed in the middle of the room where the dehumidifier was installed for reasons mentioned in the next section. As will be evident from later measurement results, the chosen dehumidifier sizing appears to have been appropriate.

2.3 Choice of set point for relative humidity

The selection of the setpoint for controlling relative humidity was discussed. Critical levels are defined in the literature for heated buildings, primarily aimed at reducing the risk of mold growth. However, unheated buildings (heritage sites) have experienced climate variations before, although condensation may have occurred less frequently during winters in the past. The buildings tolerate higher humidity levels when it is cold outside (below zero degrees). For example, Table 1 shows that the average relative humidity of outdoor air is over 80% during a typical winter in Söderhamn.

A literature review by Johansson et al. [3] summarizes that wood and wood-based materials have a critical moisture level for microbiological growth at 75–80%. Materials contaminated or soiled may have lower critical levels. Hukka and Viitanen [4] imply that mold growth risk reduces significantly when temperatures drop towards zero degrees Celsius. The supplier of the dehumidification equipment suggested control with a setpoint at 70%, but this was considered to entail a significant operating cost and might provide an unnecessarily large margin to the condensation conditions. Therefore, a setpoint for control was initially set at 75% (on October 13, 2022) and then raised to 80% (on October 20, 2022), to see if this would lead to relative humidities near 100%, especially locally where air does not circulate and in the vicinity of (decorated) surfaces.

The RH sensor for dehumidifier control was placed in the dehumidification room since this was the only room where dry air was not supplied. The control automation involved triggering the dehumidifier in "on" mode when the sensor signal exceeded 80 % and in "off" mode when the signal dropped below 78 %; i.e. with 2 % deadband.

2.4 Distribution of dry air

Installation of dehumidifiers and air distributors was done to address seasonal issues (few or no visitors during the winter months – but removed entirely during the tourist season, i.e. summer months). The dehumidifiers were placed in plastic trays on tables near windows, where single windows could be replaced with chipboards. Two holes were drilled in the chipboards for the intake of outdoor air and the exhaust of humid air. Fig. 4 illustrates one unit's placement on a table and the adjoining dry air distribution system.

Fig. 4. Picture of a dehumidifier located next to a window with chipboard for air intake and exhaust. Flexible ducts distribute dry air to adjacent zones. To the right, the controller air-RH is mounted on a rod.

To distribute the dehumidified air, a branching of spiral pipes was installed, and flexible ducts were connected for further air distribution to ensure even dried-air distribution in the spaces and enhance mixing of the room air.

Throughout the testing period, all interior doors were fully open, and there was complete openness between the floors in the stairwell. The ductwork allowed the dry air to be directed easily in the room. By placing the backside of the outlet near a wall and directing the outlet at a 30-45° angle above the floor, the risk of drying out nearby objects was avoided.

To achieve roughly equal dry air supply in all rooms, transition fittings of three different dimensions were fitted to the air outlets. Fig. 5 shows an example of the installation of air outlets for the supply of dry air, with a larger outlet diameter mounted the farther the outlet is from the dehumidifier.

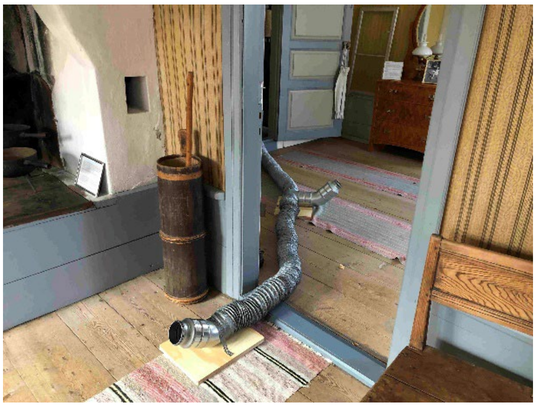

Fig. 5. Example of the dry-air distribution system.

The distribution layout at the two floors of the building is illustrated in Fig. 6.

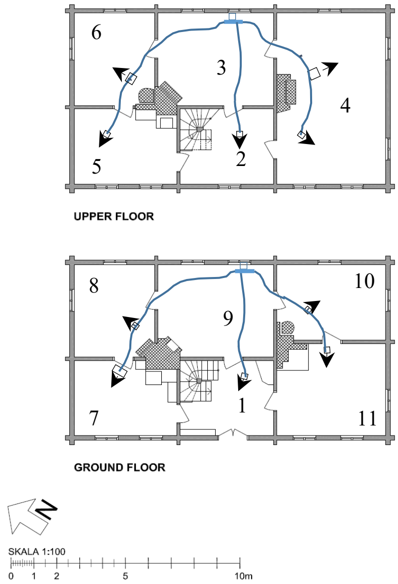

Fig. 6. Floor plan illustrating the placement of dehumidifiers and assembly for the distribution of dry air. Arrows indicate flow direction of the dry supply air. Sizes of diffusers and dehumidifiers are not to scale.

2.5 Measurements

2.5.1 Temperature and relative humidity

An essential part of the project was to verify that the dehumidification worked as intended. For this reason, climate loggers (sensors with data storage) for temperature and relative humidity were placed in various locations in the building and as well as outdoors. In parallel, there were a few online-monitoring sensors from a long-term project (monitoring climate change related effects on the World Heritage buildings). The characteristics of each measurement system are summarized in Table 2.

Table 2. Measurement systems used.

System	Mitec SatelLite T&RH-logger	Jeff Electronics/ Produal
Operation	Battery Memory	Battery Online
Accuracy Temp	±0,4 °C within -40–80 °C	±0,5 °C
Accuracy RH	± 3% within 10–95%	± 3% within 10–95%
Sampling rate	10 min average	10 min average
Battery life	~0,5 years	~2 years*

**Sensor equipped with extra battery*

The T&RH loggers were calibrated before placement, and adjustments have been made accordingly. They could be placed freely (at suitable measurement points) since the measurement period did not include visitors.

The Jeff sensors have been in place since 2016, operating year-round. This required placing them where they were not visible to visitors, which may affect the representativeness of the measurements at this location. In other words, the measured values might be slightly higher or lower than the room temperature and humidity intended for measurement.

2.5.2 Air change rate

Measurement of the local mean age of air in the Erik-Anders building was conducted using a passive tracer gas technique, following ISO 16000-8 [5]. This involves the emission of a specific tracer gas (C_6F_6) in very small quantities proportional to the room volumes (about 10 µg/h) from small diffusion tubes placed in all rooms of the building. In the same rooms, samplers (of similar size to the diffusion tubes) containing activated carbon passively absorb the tracer gas from the air. Based on the amount of absorbed tracer gas (analyzed later in a laboratory), the local mean age of air and the air exchange rate can be calculated. Tracer sources and samplers were placed in the Erik-Anders building from January 13, 2023, to February 22, 2023, providing an approximate average air exchange for this period.

2.5.3 Dehumidifiers' power consumption

The dehumidifiers were equipped with timers indicating accumulated operating time. To determine power consumption and assess how the dehumidifiers' activity varied over time, their power consumption was measured using current clamps (Toleka AB, Flex current clamps) connected to a logger (AT40, Mitec instrument AB, Sweden) recording minute averages. Temporary, more precise measurements were performed using a Fluke 1736 Power Logger.

3 Results

In order to indicate how the indoor humidity typically varies wintertime in the studied kind of unheated farmhouses, Fig. 7 shows measurement data from Erik-Anders the winter 2021-2022, i.e. one year before the dehumidification test year, as well as from a similar farmhouse, Kristofers, being in the same region and with data from 2022-2023, i.e. parallel with the tests at Erik-Anders. Measuring position is centrally in the buildings. The graphs show RH values varying roughly in the range 75-100 %, with some peaks at or near 100 %, indicating occasional condensation risk. Historical data from a few years previous to these indicate similar patterns.

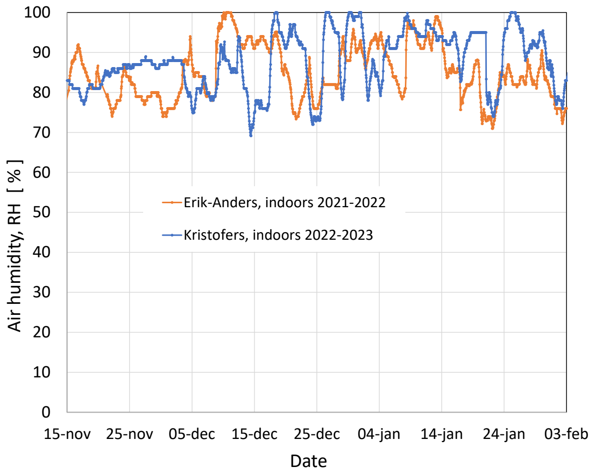

Fig. 7. Indoor air humidity variation wintertime without dehumidification: in Erik-Anders the previous winter and in a parallel farmhouse (Kristofers), resp.

Fig. 8 and Fig. 9 show air humidity variations in all rooms upstairs and downstairs, resp., plus outdoors, during the riskiest period as to condensation, Nov 15th – Feb 1st. Apparently, outdoor RH was quite high during this period, almost always staying above 90 % and often reaching 100 %. Indoors, RH chiefly stayed around 70-80 %, with a few peaks around 90 %, notably in the upstairs kitchen and ground floor bedroom (rooms 5 & 10 in Fig. 6). The outdoor temperature during this period was often near or below 0 °C (minimum around -20 °C).

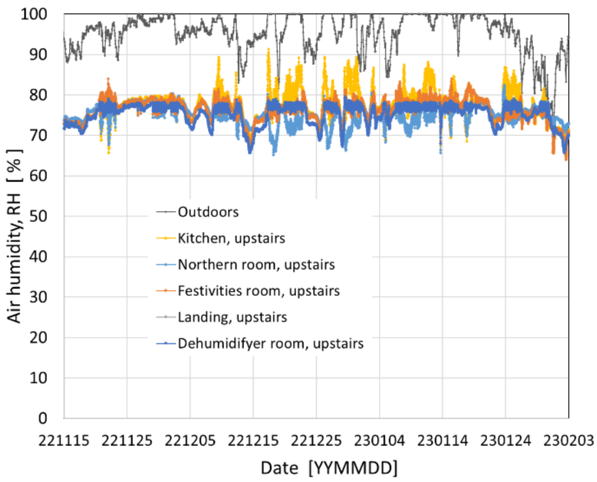

Fig. 8. Air humidity variation on upper floor.

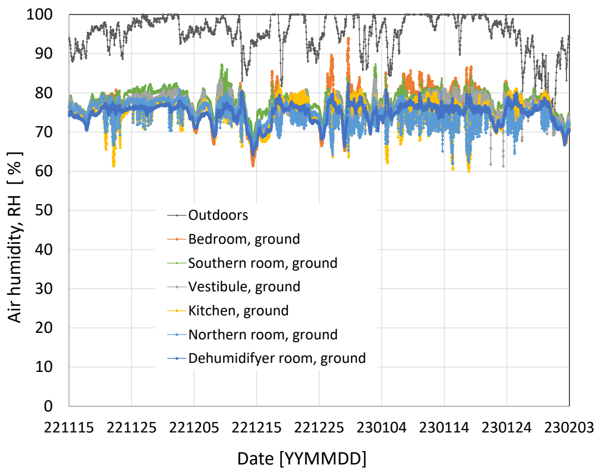

Fig. 9. Air humidity variation on ground floor.

Thus, overall it seems the dehumidification installation managed to keep the max-80%-limit pretty well. Although a few higher peaks occurred, chances seem good that condensation was avoided, at least near the points of measurement.

At the occasion of an activation of a dehumidifier, i.e. RH reaching 80 %, it was typically running according to the pattern in Fig. 10; i.e. intermittent running at roughly 20-30 min intervals, whereof active 5-15 min. As can be seen, steady-state current was at around 6.3 A while startup peaks were higher. The 1-min averaging dampens these peaks, in reality reaching about 35 A a short moment. Thus, the electricity supply, incl. kind of fuses, needs consideration at the installation.

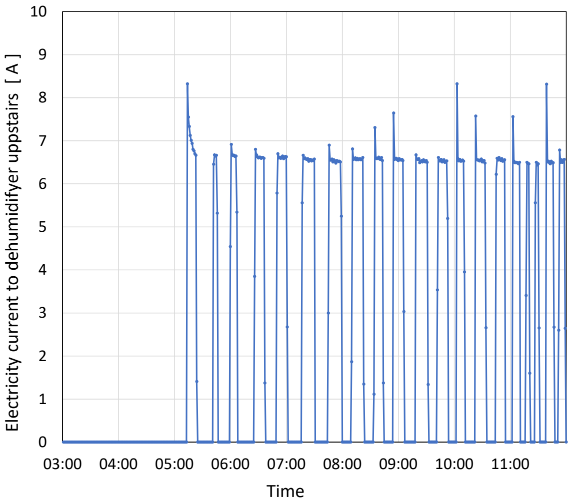

Fig. 10. Electricity current to dehumidifier upstairs on 26th of Dec 2022.

The most active periods of the dehumidifiers were in December-January, when they were active about 10 % of the time. Even a bit more intense dehumidifier running than in Fig. 10 was occasionally observed, with both dehumidifiers active simultaneously. Hence it seems the capacity of both units were needed at times. The electrical energy supplied to the dehumidifiers during the whole winter season was in total 580 kWh (283 kWh upstairs, 297 kWh on ground floor).

The measurements of air change rate in the building yielded an average of 0.76 ±0.04 ACH, with rather small variation between rooms: Std=0.12 ACH, Min=0.60 ACH, Max=1.02 ACH. Thus, the magnitude was similar to previous results attained in two other of the heritage farmhouses – 0.6 and 1.0 ACH resp., as previously mentioned.

4 Discussion

In naturally ventilated old timber houses like the studied Erik-Anders, the air infiltration rate – here quantified as measured air change rate – is crucial for the occurrence and severity of condensation on indoor surfaces, as well as for the required capacity of dehumidifiers. Since similar air infiltration rate as that of Erik-Anders (0.76 ACH) has been measured in two other of the heritage timber buildings, it is likely that similar condensation risks exist in these and other similar unheated and untight buildings in comparable cold climate. It is also probable that a similar solution with sorption dehumidifiers as that presented here will work in these buildings.

In the present case study, dry air from the dehumidifiers were distributed to all rooms, except the two rooms where the dehumidifiers were installed. The air suction at the dehumidifiers promoted the distributed air to return to these rooms, thereby reducing RH there as well. As a result, the indoor air humidity proved rather homogeneous at the setpoint 80 % during dehumidification. However, as shown above, the tested solution entails considerable installations for the air distribution system, which requires some effort and may make the interior aesthetically unappealing to potential visitors. Although the heritage farmhouses in question rarely are visited during cold wintertime, it would be interesting to know if a reduced installation with fewer supply points of dry air could still achieve a good enough RH reduction through diffuser induced and natural room air mixing. Extended tests in this regard are presently (winter 2023-2024) ongoing in Erik-Anders.

An alternative method to dehumidification for reducing indoor humidity is *protective heating* through the installation of some (electrical) heaters. However, this is an energy consuming method, which also has other disadvantages, which soon will be revealed. By utilizing the measured air change rate in the Erik-Anders building and assuming three different indoor setpoint temperatures (+5, +10 and +15 °C, respectively), the required heating energy to compensate for ventilation heat losses was assessed for a typical winter season (October-March). Hourly outdoor temperature values were obtained from a nearby meteorological station (Söderhamn, Swedish Meteorological and Hydrological Institute). The winter season 2022-2023 (t=4368 hours) yields an average temperature of $\overline{T_e}$ =+0.4 °C. With these parameters inserted into Eq. 1, the estimated required energy for heating infiltrated air (E_{inf}) to indoor temperature setpoint (T_{sp}) is shown in the Table 3 below.

$$E_{inf} = \frac{n_{inf} \cdot V}{3600} \cdot \rho \cdot c_p \cdot \left(T_{sp} - \overline{T_e}\right) \cdot t \qquad (1)$$

where

n_{inf} is the air change rate (ACH)
V is volume enclosed by the building envelope (m³)
ρ is the density of the air (kg/m³)
c_p is the specific heat capacity of air (J/(kg·K))

Table 3. Estimated heating energy, E_{inf}, to attain a certain indoor temperature setpoint when only compensating for air infiltration heat losses.

Indoor temperature setpoint (°C)	Required heating energy (kWh)
+5	2230
+10	4660
+15	7100

When comparing with the 580 kWh resulting from the presented dehumidification venture, protective heating appears to be a much more energy consuming method. However, only *ventilation* losses have been included in Table 3; *transmission* losses through the building envelope is likely to be of similar or even higher magnitude. In total, protective heating appears to be at least 10 times more energy consuming than dehumidification. While protective heating does yield a more comfortable climate for occasional visitors, unfortunately, it may also attract unwelcome guests. Rodents are drawn to warmth and may settle in heated buildings, while insects thrive in humid and warm environments. For example, carpenter ants prefer warm places, especially in moisture- and decay-damaged wood, and striped woodborers damage houses, furniture, and other wooden items if the wood's moisture content is suitable. Therefore, pest control becomes essential for this alternative method. Additionally, with protective heating it needs to be ascertained that the indoor air doesn't become *too* dry. The old timber houses in question have historically been exposed to relatively humid air, and a sudden change to drier air might result in material deterioration, such as cracks in wooden objects and flaking paint. Finally, there are aesthetic aspects to consider with electric radiator, as they are not contemporary and require cable distribution, which may detract from genuine appearance for potential visitors.

5 Conclusion

Sorption dehumidifiers installed in an unheated and naturally ventilated historical timber building proved functional in reducing indoor RH enough to avoid condensation throughout one tested winter season. However, locally and temporarily somewhat enhanced RH peaks occurred, possibly due to unfavourable transient wind and/or stack conditions. In future studies, it seems advisable to include even more local RH measuring points in remote corners, etc., where air may remain stagnant and humid. It would also be interesting to test if simpler ductwork for dry air distribution could be applied, still achieving sufficient RH reduction in all critical indoor spaces. The measured air change rate of around 0.8 ACH was of the same magnitude as previously noted in two similar historical farmhouses, making it likely that the tested dehumidification system is applicable to these types of buildings. The electrical energy supply of 580 kWh to the dehumidifiers during the whole winter season appears to be at least 10 times less than an electrical protective heating installation would require.

Acknowledgements
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