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# Development of smart control system for leakage warning in compact roofs

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# Development of smart control system for leakage warning in compact roofs

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**Abstract**. Smart Sensor technologies to monitor temperature and moisture conditions in building components, can be used to give automatic warnings for abnormal high levels of moisture. Flat compact roofs are of particular interest, especially due to their vulnerability to rain leakages through the roofing membrane. Installing moisture sensors in such a roof measuring relative humidity (RH) or free water may give an early warning of rain leakages or condensation due to air leakages from indoors – before they start to get problematic. One challenge is, however, that normal moisture redistribution in the insulation layer over the season or day may give very high levels of RH in the top or bottom part of the insulation. The sensor system must be able to distinguish between these normal levels and leakage events. Together with a sensor technology and control system producer we have previously developed a semi-quantitative system that defines typical or normal RH levels in the insulation layer during the year. This system was based on hygrothermal simulations for various conditions, such as different exterior climate and levels of built-in moisture. This paper presents the preliminary findings from the further development of the system using real measurements from two pilot buildings located in Norway.

## 1. Introduction

Smart Sensor technologies to monitor temperature and moisture conditions in building constructions are under constant development [1]. Such sensors, when installed during the erection of the building, can be used to give automatic warnings for abnormal high levels of moisture. Flat compact roofs are a type of construction of particular interest to monitor, especially due to their vulnerability to rain leakages through the roofing membrane [2]. Flat roofs are for instance increasingly being used for purposes like energy generation with photovoltaics and buffering of heavy rain events (blue-green roofs), making the roofing membrane more exposed to rain leakages and any repairs after leakages more expensive. Installing moisture sensors in such a roof measuring relative humidity (RH) or free water may give an early warning of rain leakages – before they start to get really problematic and while the repair costs still are low. Condensation due to air leakages from indoors may also be discovered, particularly interesting in buildings with high indoor humidity like swimming pools. For some building owners the risk of major leakages that leads to downtime for their business cannot be accepted. For museums, archives and galleries such sensor systems may help to avoid damages on their exhibition or stored items.

One challenge with such measurements is however that normal moisture redistribution in the insulation layer over the season or day may give very high levels of RH in the top or bottom part of the insulation, without this representing a problem. Thus, a sensor system designed to give warnings or alarms must be able to distinguish between these normal levels and leakage events. Knowledge of these normal moisture levels is therefore important and can be found either through moisture measurements in real roofs or through numerical simulations with combined heat, air, and moisture models. In a previous study in this project hygrothermal simulations of compact roofs under different climate conditions were performed as a first attempt to identify these normal levels for the various seasons [1].

The main objective of this study has been to gain experience and further develop a sensor system for early leakage warning in compact roofs. The system is based on a relatively high number of wireless sensors that are placed in a grid pattern over the whole roof during construction, typically placed on top of the vapour barrier. The sensors measure the RH, temperature and free water. Together with continuous readings of meteorological data from public sources the system is designed to give warnings or alarms to the operator when free water or unnormal high RH levels occur on top of the vapour barrier or any other places the sensors are located. Through the help of algorithms that combine moisture measurements and meteorological data it is expected that the system should be able to differ between normal moisture levels and leakages. This study presents preliminary results from an analysis of measured data from two different pilot buildings. The focus has been to identify and illustrate connections between measured data, occurring climate conditions and variations over different seasons, and in the end to improve the above-mentioned algorithms.

## 2. Method

### *2.1. Pilot buildings*

Temperature, RH and moisture data from sensors installed in two flat compact roofs has been analyzed and compared to weather data from nearby weather stations. The roofs are located in Drammen and Porsgrunn in Norway and are further referred to as Roof 1 and Roof 2. The buildings were erected in 2021, the sensors were installed in February 2021 and the roofing membranes were installed during the first three weeks of March. Data from the period 22.02.2021-15.06.2022 (~1,5 years) has been analyzed.

Roof 1, which is above an office building, contains 46 sensors located at the warm side of the thermal insulation and on top of the vapour barrier, se figure 1. The sensors along the roof edge are installed at a distance of 0,6 m from the parapets. The rest of the sensors are placed symmetrically and with a space as close as possible to 5 m (depending on the extent/size of the roof). Along the parapets and around drains, mineral wool is applied instead of EPS with an extent of 0,60 m for fire safety reasons, thus sensors 1-8 is positioned near the interface between mineral wool and EPS. The total thickness of the thermal insulation is equal at the middle of the roof (~500 mm) and decreases towards the parapet (~280 mm). Roof 2 is above a workshop hall and contains 52 sensors, of which 10 sensors are located above the EPS-layer and the rest are located on the cold side of the vapour barrier. In this paper, only measurement data from Roof 1 are highlighted. The analyzed sensors in Roof 2 portrays a very similar behaviour as Roof 1 and are therefore not presented in detail in this paper.

### *2.2. Position of sensors*

Data from two groups of sensors in Roof 1 are highlighted: Sensors 1-4, 7 and 8 have the same distance to the parapet and the same insulation thickness. Sensors 9-13 are located where the thermal insulation is thickest. The groups of sensors are illustrated in figure 1, and the measurement data and warnings and alarms are presented in Chapter 3.

### *2.3. Weather data*

Climate files were created using data retrieved from Shinyweather.com [3].

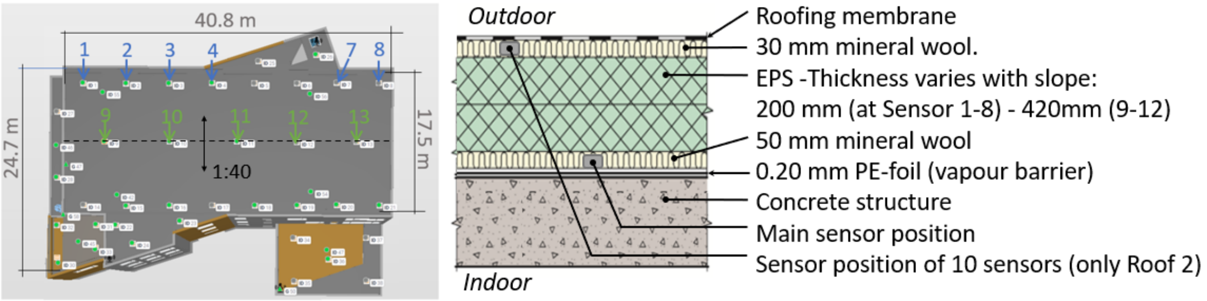


**Figure 1.** Illustration of Roof 1 including the layout of the 46 sensors (left). Illustration of position of sensors within the thermal insulation (roof 1 and 2).

### *2.4. Sensors and data system*

The into® Sensor measures the surrounding temperature, humidity, and water through three different types of sensors and transmits the data wirelessly through a Gateway to a cloud application (iCS). In iCS the data is processed and if the system finds an abnormal moisture value or an immediate leakage it warns the involved users. The into® Sensor is configured as a data logger reading the measured values in specified intervals and transmits the reading in intervals depending on chosen mode. The logging interval can be configured from every 1 minute up to 15 minutes. The into® Sensor is depicted in figure 2.


**Figure 2.** The into® Sensor are installed in building components such as a roof and measures the surrounding temperature, humidity, and water leaks [4].

Normal moisture redistribution in the insulation layer over the season or day may give very high levels of RH in the top or bottom part of the insulation. The cloud application (iCS) uses an algorithm which enables a combined assessment of weather data automatically collected from public sources and measurements of RH, temperature and free water to determine potential leakages. The algorithm must be able to distinguish between these normal levels and leakage events and is under continuous development.

The water sensor measures the electrical voltage between two electrodes located in the bottom of the sensor casing. The water sensor transmits a tensor of 3 volt and thus measure a voltage between 0 and 3 V. High values indicates that water is present between the two electrodes as a result from either a leak or condensation and results in a warning or alarm. When no water is present the voltage is low or zero.

### *2.5. Reliability of the system*

The impact of sensor failures on the reliability of the whole system depends on the complexity (size, layout, implementations) of the roof that is investigated and the amount and position of the sensors. The optimal amount and position of the sensors will be investigated thorough the project by comparing measured data of sensor where leaks have occurred and data of surrounding sensors.

### *2.6. Accuracy of sensors and corrections*

While the temperature and free water sensors are relatively stable and insensitive to drift, the RH-sensor on the other hand is more unstable. The accuracy of the RH-sensor is according to the product data sheet

±3% RH) [4]. However, when the RH in the roof becomes high, the sensors become unstable and the measured RH values becomes inaccurate. The error increases with increasing RH. When exceeding 95 %, the measured RH show values between 95 % and up to above 100 % (readings up to 120%). Condensation or free water occurring on the sensor may also cause the measured data value to shift rapidly from high (>100 %) to very low (<20 %) or even stop to function for periods. This unstable behaviour is problematic when data from several sensors is to be viewed simultaneously. Latest data sets are therefore compensated for this behaviour by correcting the logged data to 100 %. In some of the analysed data, however, this behaviour is not corrected for.

It should however be noted that the purpose of the RH-sensors is not necessarily to measure the correct RH, but that they can be used to identify typical seasonal and daily moisture redistribution patterns. This means that the type of RH-sensor embedded in the into® Sensor was chosen as a payoff between the cost of sensor and robustness and reliability. Another part of this project is also to get experience with the sensor regarding drifting, instability and accuracy when exposed to the sometimes-high moisture levels in compact roofs. Especially we should mention the installation period when the sensors often are directly exposed to rain or the first months after with possibly free water from high levels of built-in moisture.

## 3. Results

Hourly time series data was obtained from the sensor technology and control system producer. These were used to create graphs of the measured variations in temperature, RH, free water (V) and climate (normal rain, outdoor air temperature and global radiation). Graphs were first created for the entire measurement period and for all the sensors in the two pilot buildings.

The two roofs and sensor positions were evaluated to consider: 1) the size and layout of the roof, 2) the design/build-up of the roof structure, 3) thickness and type of thermal insulation and 4) the slope of the roof. Based on the evaluation, the sensors were divided into smaller groups (4-8 sensors) with common denominators, such as equal thickness and type of thermal insulation and distance to the parapets. Figures with graphs for temperature, RH and climate for the smaller groups of sensors were created and the variations within the different groups compared to each other for the entire measured period (1.5 years). Figures where then compared to graphs showing normal rain, outdoor air temperature and solar radiation for the entire measuring period. Figure 3 show an example of this for one of these smaller groups (sensors 1-8 in Roof 1), where the measured RH and free water during the measurement period of 1.5 years are compared to weather data.

When looking at the measured RH for sensor 1-8 we can see that during the first seven months the readings are very unstable, jumping from RH readings above 100% to below 20% and up again in short time intervals, or being totally nonfunctional in periods. This is due to relatively high levels of built-in moisture, probably meaning the RH is somewhere above 95% during the first months, thus making the sensors unstable. In addition, the sensors were installed during rainy weather, meaning the RH-sensors could have experienced free water, which also makes them unstable. This is according to the system producer a rather typical picture for the RH during the first months after installation, meaning they do not send automatic warnings or alarms to the operator in connection with the RH-readings (or the water sensor) the first months, but instead focus on manual analysis of the water sensor readings to look for any signs of leakages. However, as shown in figure 3 the RH readings become more reasonable after the first seven months, and it is possible to apply automatic warnings/alarms.

Regarding the water sensor readings shown in figure 3 we can see that they fluctuate quite a lot during the first seven months. This is mainly due to built-in moisture and is also a typical picture for the water readings during the first months. Since there is little meaning in giving warnings or alarms for free water due to built-in moisture, also the water sensor readings are typically analyzed manually this first period. High readings such as for sensor 2 in June and July, could indicate a rain leakage, but could also possibly be explained by built-in moisture in the insulation layer being redistributed downwards to the vapour barrier during the summer. Based on experience a warning level at 0,36 V (yellow line) and an alarm level at 1,76 V (red line) is used. Values above the warning level indicates that there is some condensation or free water present, but not necessarily a water leak. Values above alarm level indicates free water and minimum a water film present, i.e. a strong indication for a leakage. In this case, an inspection of the roof in June revealed that the high water readings by sensor 2 were in fact caused by a leak through a hole in the roofing membrane, which was immediately repaired.

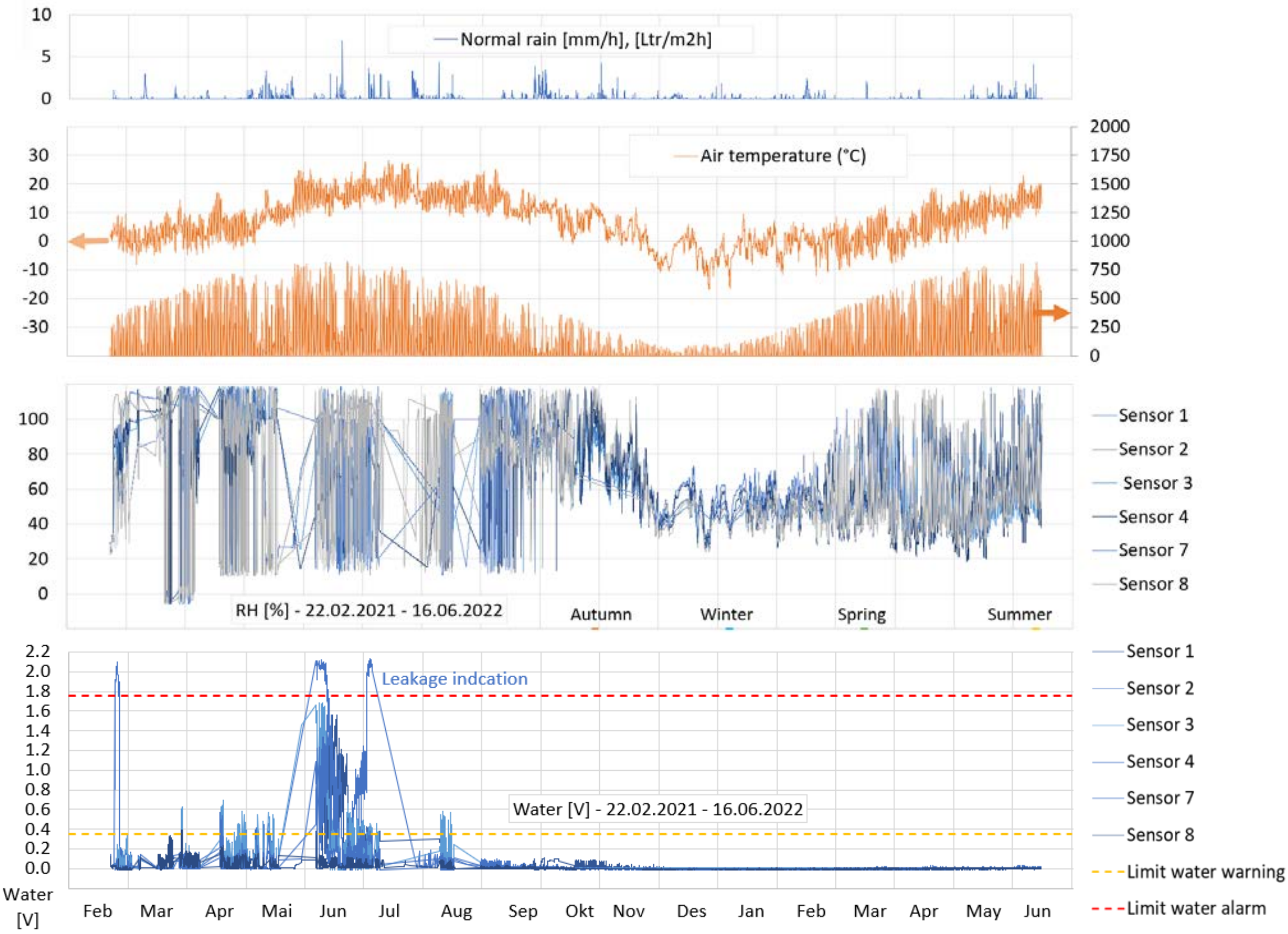


**Figure 3.** Normal rain, outdoor air temperature and solar radiation (upper three graphs), and RH and water sensor readings at the interface between vapour barrier and insulation (lower two graphs).

Four different periods of one month each were then selected from the annual overview, i.e., autumn, winter, spring and summer. Based on this overview, one week was selected from each period of the year with somewhat different outdoor temperatures and RH variations. As the overall comparison showed that the first seven months of the measurements were largely influenced by the built-in-moisture, with very unstable and unreliable RH-readings, this selection started first in October 2021. Based on this comparison, three-day periods from the four seasons with varying solar radiation were selected and included in an illustration to show the impact of solar radiation on the RH. An example of this is shown in figure 4 for the two sensor groups. During the autumn, we see that the RH-readings is still relatively high owing to the built-in moisture, perhaps still making automatic warnings and alarms in connection with the RH readings difficult. However, for the winter season we see that the RH is rather low, indicating that the main portion of the built-in moisture has dried. It is then possible to apply automatic warnings and alarms, also for the RH. As warning and alarm levels 90% and 95% RH is used.

For the spring and summer we do however see that the daily RH-cycles during sunny days gives a natural RH-level above 95% at midday for the first group of sensors (sensor 1-8). To account for this, no warnings or alarms is given based on the RH-readings according to the following algorithm: between

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6AM and 10PM in the period April to August no warnings or alarms are given, if at the same time the meteorological data show that there has been less than 1 mm rain the last 6 hours and the outdoor temperature is above 10 C°. As a part of this project this algorithm is under continuous development, and it is intended to apply machine learning to refine these algorithms. The second group of sensors (sensor 9-13) do however not experience the same high RH levels during sunny days in spring and summer. This is most likely because sensor 1-8 are located close to the 0,6 m band of pure mineral wool along the parapets, meaning that the daily redistribution of moisture between the top and bottom of the insulation is faster than for the part of the roof with the more vapour tight EPS. In addition the insulation thickness at sensor 9-13 is almost double of that at sensor 1-8. This also illustrate that roofs with different build-up may need different adaptions of the warning and alarm algorithms.

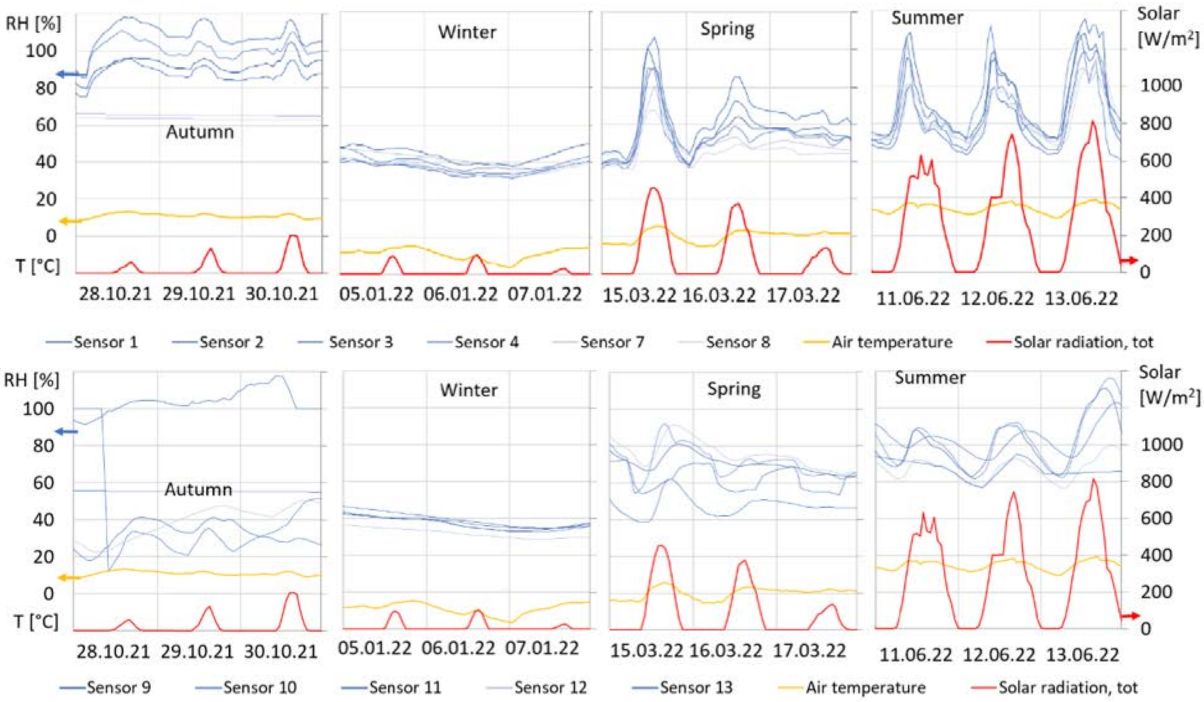


**Figure 4.** Variation in RH at the interface between vapour barrier and insulation for three days during autumn, winter, spring, and summer, shown together with global radiation and outdoor air temperature. The upper graphs show sensors 1-8 where the thermal insulation is ~280 mm and the lower graphs show sensors 9-13 where the thickness is ~500 mm and EPS is used. The four periods are illustrated along with the RH-diagram in figure 3.

Further on, data from the water sensors were analysed in detail. Figure 3 illustrates the measurements of free water for one of the sensor groups (sensors 1-8, Roof 1). Figure 3 clearly illustrates how the high built-in moisture results in high RH during the first seven months. During this period, many small readings (<0,37 V) and some medium readings (0,37-1,75 V) were measured on the free water sensors, with the exception of one sensor (sensor 2) which showed high readings repeatedly (>1,75 V). Among the sensors in the group on the middle of Roof 1 (sensor 9-13), there were also two sensors resulting in high readings (9 and 12), see figure 5. Owing to the high readings, the roof was inspected in June and leaks were detected close to sensor 2, 9 and 12. The damage was repaired and "ventilation caps" were mounted on the membrane in the beginning of July to speed up drying. As shown in figure 3 and 5, the roof around sensor 2, 9 and 12 dried effectively and remains dry during the rest of the measured period. Figure 5 and 6 illustrates how the measured data resulted in warnings and alarms for sensor 9, 12 and 13. There were no leakages at the location of sensor 13, it only experienced the same level of high built-in moisture as the other sensors. Note that the alarms and warnings the first seven months were not sent directly to the operator, but analysed manually.

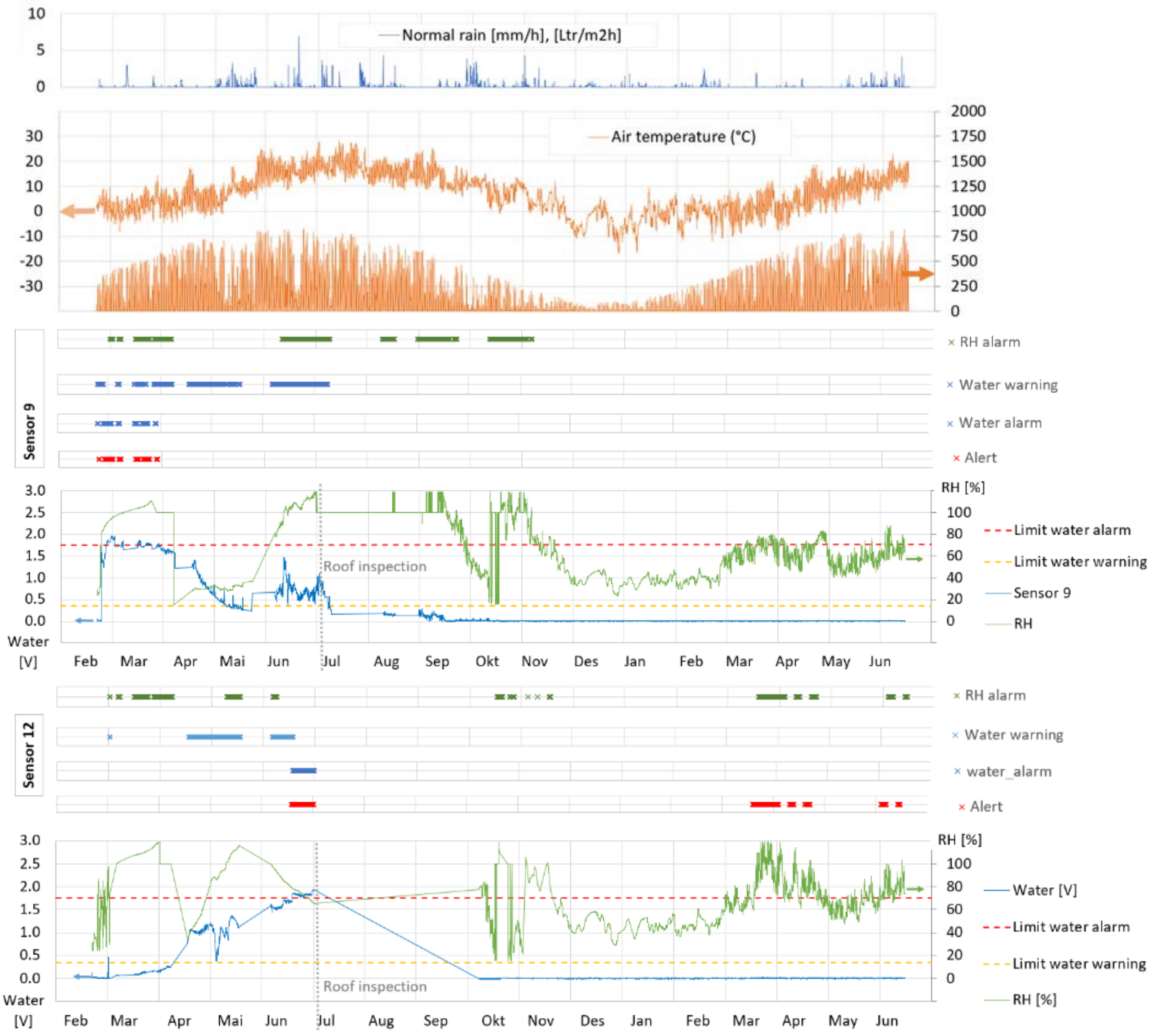


**Figure 5.** Illustration of how the free water and RH sensors resulted in warnings and alarms which lead to the detection of the leaks for the sensors 9 and 12.

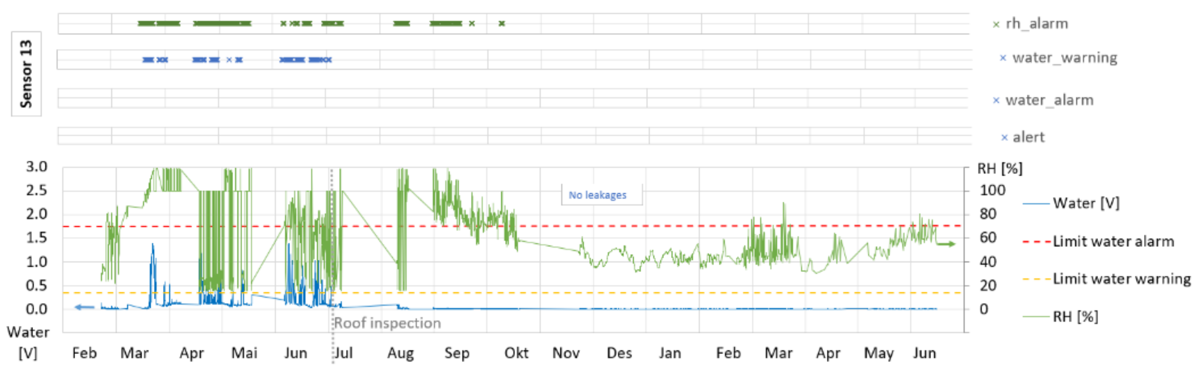


**Figure 6.** Illustration of measured data, warnings, and alarms for one sensor were there were no leakages. The built-in moisture results in RH alarms during the first 7-8 months.

## 4. Discussion

This study presents preliminary results from an analysis of measured data from two different pilot buildings. Some contexts between measured data, occurring climate conditions and variations over different seasons has been identified, and may be used to improve the systems algorithms for issuing warnings or leakage alarms to the operator.

As illustrated in figure 3-6, the high RH caused by the built-in moisture makes it difficult to detect water leaks through the roofing membrane up until the moisture has dried out. Owing to this deficiency, leaks caused by construction errors could be mistakenly interpreted as built-in moisture and potentially go undetected for a long time. The RH-sensor becomes unstable and unpredictable when exposed to free water as clearly illustrated in figure 3. Using a RH-sensor which is more stable at higher RH-levels may contribute to make the RH measurements more stable and thus make it easier to determine whether the free water sensor measures built-in moisture or an actual leak.

Repeatedly high readings on the free water sensors (>1,75 V) is a strong indicator that a leak through the membrane has occurred. Since many of the sensors portrayed high readings in June, the roof was inspected and leaks were discovered for sensors 2, 9 and 12. The leaks were repaired in the start of July. During the rest of the measuring period the reading remained very low (~0 V).

The RH in the roof is, as mentioned, high and unstable for the first seven months (February to October). In the following colder months, the RH is significantly reduced, remaining low (<80) until spring. As illustrated in figure 4, RH is strongly influenced by the solar radiation. The algorithm should therefore be trained to overlook daily elevated fluctuations in RH within certain reads owing to solar radiation. High readings of the free water sensors at daily RH fluctuation should not result in alerts.

## 5. Conclusion

This study illustrates how a sensor system that measures RH, free water, temperature and compares to weather data can be used to give early warnings of leaks in building components, such as roofs. This can be particularly useful in, for example, compact flat roofs, due to their vulnerability to rain leakages through the roofing membrane. Measuring RH in such roofs are a particular challenge in regard to sensor technology, due to possible high levels of built-in moisture and the normal seasonal and daily variations that may give periodic RH-levels close to 100%. This study shows an example how this could be handled to avoid unnecessary warnings and alarms to the operator.

## 6. Acknowledgments

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