REPORT
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D.6.5 Description of a certification scheme on "verified building performance”

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Jan Steiger, Jessica Grove-Smith, Dr. Benjamin Krick, Luca Müller, Wolfgang Hasper

CONTACT

Jan Steiger
Passive House Institute
+49 (0) 6151 826990 | jan.steiger@passiv.de

OUTPHIT – DEEP RETROFITS MADE FASTER, CHEAPER AND MORE RELIABLE
outPHit pairs such approaches with the rigour of Passive House principles to make deep retrofits cost-effective, faster and more reliable. On the basis of case studies across Europe and in collaboration with a wide variety of stakeholders, outPHit is addressing barriers to the uptake of high quality deep retrofits while facilitating the development of high performance renovation systems, tools for decision making and quality assurance safeguards.
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ABSTRACT

This report outlines the concept developed to measure and evaluate the performance of deep retrofit projects implementing the outPHit methodology in the field. Efforts are made to streamline and automate most steps in order to make the process of building performance evaluation, with sound consideration of measuring uncertainty, accessible to new target groups, such as architects and engineers, or even builders: Currently no systematic feedback on the success of buildings and building concepts in the field exists for them, a missed opportunity for learning and continual improvement in the industry. A low-cost data acquisition system based on LoRa radio communication is outlined and tolerable measuring uncertainty of sensors discussed. Data collection, pre-processing and final evaluation and implemented within an on-line database are illustrated: Measured data is used to update a detailed monthly energy balance calculation with actual boundary conditions and thus provide a yardstick to understand the metered energy consumption. An outline is given to illustrate the uncertainties inherent in comparisons of measured and calculated values. Conclusions are derived regarding the development of certification criteria in *D6.7 : Certification Criteria for "verified building performance"*. A procedure to systematically evaluate elementary living quality parameters has been identified.

CONTENTS

AIM AND SCOPE

Aim and scope of the outPHit project's "Verified Performance" programme is to verify the performance of a deep retrofit in the field as a standard measure of final approval. If carried out by an independent party that both customer and supplier have previously agreed upon, the process may offer an unbiased analysis to both.

From the quality assured design process a third-party-certified energy model of the building is available, that can be used to predict the building's performance under known boundary conditions. During the building´s efficiency design stage, standardised values must be assumed for climate, occupancy, electricity consumption by users and other factors. In hindsight, however, most of these variables can be known from measurements and be used to update the energy model for the period in question.

If a good agreement of the expected consumption, as predicted by the updated energy model, and the measured consumption, is found, the probability of major flaws in the building's fabric, technical systems or their commissioning is low. Due to inevitable measuring uncertainty, unknown boundary conditions and building use, the match cannot be expected to be perfect. Uncertainty analysis can, however, point to the band of results which still indicate agreement. Careful selection of sensor specifications will ensure this band is sufficiently narrow to achieve a meaningful result.

PREREQUISITES

For the post occupancy evaluation to work well, it is recommended for the project to meet the following pre-requisites:

- A careful building energy efficiency design with third-party quality assurance makes a detailed and reliable energy model (e.g. from [PHPP10]) available.
- Careful site supervision ensures compliance with design.
- Prefabrication reduces site work and relocates production to an well controlled environment.
- Qualified experts and tradespersons are tasked with the remaining work.
- The airtightness has been measured for pressurisation and depressurisation (EN ISO 9972, NA Germany) and the residual leakage is very low ($n_{50} \le 1.0\ h^{-1}$ for retrofits or $\le 0.6\ h^{-1}$ for new builds).
- Systematic commissioning, including flow balance adjustment, of the ventilation system guarantees air change rates according to the design of the ventilation system.
- The energy balance calculation of the project (e.g. with[PHPP10]) has been updated to the finally executed project specifications.
- With the completion of the renovation project, a third-party verification (e.g. a building certification according to the [EnerPHit] standard) confirms the fulfilment of the criteria of the efficiency standard.

DATA ACQUISITION

Transmitting analogue signals for long distances increases the noise and introduces additional causes for faults and errors. Digitizing the values as closely as reasonably possible to the location of the measurement helps minimise these undesired effects. Technology to transmit the digital data is not vital, almost any digital data acquisition system can work as the data rate is low, compared with other IT systems. GreenPHY power line communication appeals as it uses existing infrastructure (the power lines) and also provides power supply to the sensors at the same time, but unfortunately was found to be unsatisfactory in old multi-branch electrical systems. The alternative recommendation is to use LPWAN radio technology, specifically LoRaWAN (referred to as *LoRa* in this document for brevity) which operates within the EU at 868 MHz and hence in a frequency band that is not too easily attenuated within a building. The technology is easy to deploy temporally, runs on battery power for about 5 years and requires no fixed infrastructure or otherwise lost investment. Moreover, it can be delivered on site pre-configured and be easily deployed by non-expert personnel. Equipment is available at less than 100€ per node, which is crucial for economic viability of the programme. One central receiver is installed per building in order to log the messages from all sensor nodes and to relay them to a central data base. Sensors with high gain (2 dBi) external antennas are preferred for robust radio transmission. A wide range of sensors, meters, pulse counters and weather stations are available in the LoRa ecosystem, with a small number of devices meeting demanding specifications.

In cases where digital/wireless data acquisition systems already exist for other reasons it can be a consideration to use/upgrade them the monitoring purposes discussed here.

WEATHER DATA, PARAMETERS AND MEASURING UNCERTAINTY

The energy balance based analysis requires the temperature and relative humidity as well as the pressure of the ambient air to be known. Further, short wave solar radiation (global radiation) on the horizontal plane must be measured. For the later building performance analysis global radiation data is required not only for the horizontal but also for the vertical plane in four cardinal directions. This is achieved by measuring global horizontal radiation with a good grade irradiation sensor (Pyranometer) and treatment of the data within a mathematical sky model [Perez/Ineichen]. A different approach would be to directly measure all five desired components using calibrated and temperature-compensated PV-cells. Either method is subject to its particular set of uncertainties but both seem useful with regard to the required overall uncertainty.

Designation	Tentative Product	Specification	Signal/Remark
Temperature and relative humidity (0- 100 %)	Sensirion SHT85	± 1.8 % rH, ± 0.2 K	I2C digital output
Radiation shield with fan aspirator for temperature/rel. hum. sensor above	Davis Instruments 24-Hour Fan-Aspirated Radiation Shield, NovaLynx 380-283,	1.4…2.5 m/s air speed night/day	Self-contained PV-operated fan
Global horizontal irradiation per pyranometer	Kipp&Zonen CMP 6, Hukseflux EKO MS-60 Apogee SP-510-SS	ISO 9060:2018, class A instrument beneficial, class B recommended, class C tolerable	Analogue/precision amplifier/ADC Thermopile type preferred for temporal stability
Irradiation per calibrated PV cell (global horizontal or vertical)	NES SOZ-03	± 5 % of daily integrals	Low long-term drift, calibration good for 3 years
Air pressure	Bosch BMP280	± 1 hPa	I2C digital output
CO_2 concentration	Sensirion SCD41, Sensirion STC31	±(40 ppm + 5 % of value)	I2C digital output

Table 1: Specifications for meteorological parameters

INDOOR AIR CONDITIONS, PARAMETERS AND MEASURING UNCERTAINTY

In order to acquire a limited yet useful set of data on the indoor air conditions for both energy and living quality assessment a combination of air temperature, air relative humidity, and CO_2 is proven. Air pressure is measured in addition in order to calibrate the CO_2 sensor and avoid a specific setup of the sensor for the exact location height above sea level.

Designation	Tentative Product	Specification	Signal/Remark
Temperature and relative humidity (0- 80 %)	Sensirion SHT35	± 1.5 % rH, ± 0.1 K	I2C digital output
CO2 concentration	Sensirion SCD41, Sensirion STC31	±(40 ppm + 5 % of value)	I2C digital output
Air pressure	Bosch BMP280	± 1 hPa	I2C digital output

Table 2: Specifications for indoor air parameters

Demands can largely be streamlined with the specifications of the weather data acquisition and hence a standardised equipment can be used.

ENERGY USE, PARAMETERS AND MEASURING UNCERTAINTY

All meters for energy used within the thermal envelope of the building must be sampled. Depending on local conditions some sub-metering can be useful, e.g. for heat-pump systems, solar thermal hot water systems etc. To standardise the data acquisition, it is useful to use meters with pulse output as are available for electricity, heat, gas or water. If meter data beyond the energy count is desired, the Meter bus (M-Bus as per EN 13757) can be used to interface the more comprehensive meter data sets; Gateways for LoRa integration exist, or a stand-alone M-bus network could be operated. Moreover, an increasing number of meters can generically provide data wirelessly over LoRa. For any heat pump systems a sub-meter for electricity (input) and a heat meter (output) are recommended in order to determine the heat pump performance. If cooling via water wells or ground probes is used, a heat meter is also very useful here.

Designation	Tentative Product	Specification	Signal/Remark
Electricity	-	class B (+/- 2 %), class C (+/- 0.7 %) beneficial, [2014/32/EU]	Pulse output
Gas	-	1.5% [EN 1359]	Pulse output
Heat	-	5% (effective) Class 2 [EN1434]	Pulse output, generic LoRa meters also available
Pulse counter	elsys.se ELT lite; solvera-lynx.com ComBox.L CI	-	Battery powered LoRa Pulse Counter
wMBus to LoRa Gateway	IMST GmbH Wireless M-Bus Range Extender	Calendar function to limit data rate	Battery powered
M-Bus to LoRa Gateway	Iot factory M-BUS to LORAWAN Converter	Entire M-Bus frames can be forwarded	Up to 10 slaves

Table 3: Specifications for metering

MEASUREMENT INTERVALS

Weather and indoor air parameters shall be sampled at regular intervals, both mean and instantaneous values are possible as long as the interval is not too long. The interval shall be the same for weather and indoor data sampling and shall not exceed 20 min. Otherwise the dynamics of the situation is lost. Less than 10 min. will normally be useless and, on the contrary, make the dataset unnecessarily large and pose high demands on the scaling functionality of a data base. Meters shall be sampled at least monthly, on the beginning of the 1st day of the month. If automated equipment is used an interval of 3 hours is reasonable but not mandatory. Since the number of meters is usually low, it is also possible to apply the same standard interval as for room and weather sensors.

Parameter	Interval	Remark
Weather: Temperature and relative humidity	15 min (10-20 min)	mean or momentary
Weather: Global horizontal radiation	15 min (10-20 min)	mean or momentary
Weather: CO_2 concentration	15 min (10-20 min)	mean or momentary
Weather: Air pressure	15 min (10-20 min)	mean or momentary
Indoor: Temperature and relative humidity	15 min (10-20 min)	mean or momentary
Indoor: CO_2 concentration	15 min (10-20 min)	mean or momentary
Indoor: Air pressure	15 min (10-20 min)	mean or momentary, internally used for CO_2 sensor calibration, need not be transmitted
Energy Meters	3 hour	At least manually read on the 1st of each month

Table 4: Measuring intervals

NUMBER OF SENSORS

Residential Buildings

For small buildings up to 30 dwelling units each dwelling unit shall be measured with at least one sensor station located in a central spot that is representative of the whole. For larger buildings it is useful to follow the same rule. However, a statistically significant result might be achievable with less than 100% coverage, if at the cost of reduced robustness. Measured dwelling units must nevertheless be evenly distributed across the entire volume of the building in order to represent the average conditions and the impact of variations in solar exposition, user behaviour, fabric heat loss, and other variations in the best possible way.

For buildings with more than 30 dwelling units the required minimal number of measured dwelling units *n* may be estimated for a total number of dwelling units *t* with the following formula. Any decimal fractions are always rounded up to full integer numbers.

$$n = 30 + \frac{1}{3} * (t - 20)$$

Formula 1: Measured dwelling units in buildings with more than 20 dwelling units

In addition to this core equipment one sensor shall be placed in each stairwell located within the thermal envelope, at half the height of the thermal envelope. In unheated basements one auxiliary sensor shall be placed in a representative spot. For basements within the thermal envelope one sensor shall be placed for each 100 m² of basement floor area.

Non-Residential Buildings

All areas within the thermal envelope of non-residential buildings are divided into zones that are distinct by storey, orientation, solar exposition, usage, occupancy, internal heat gains and regular room temperature. For each zone, as a rule, 3 sensors shall be placed evenly spaced in order to sample the representative mean conditions. The number of sensors may be reduced for small areas. There shall never be less than 1 sensor per 100 m².

In addition to this core equipment one sensor shall be placed in each stairwell located within the thermal envelope, at half the height of the thermal envelope. In unheated basements or parking spaces one auxiliary sensor shall be placed in a representative spot. For basements within the thermal envelope one sensor shall be provided for each 100 m² of basement floor area.

An aid to determine the required numbers of sensors and meters is documented in the appendix of this document.

SENSOR PLACEMENT

Weather Sensors

Placement on the roof on a mast clear of shading objects/above ridge height and as far as practically possible from the (hot) surface of the roof.

The Pyranometer/irradiation sensor must be carefully levelled and mounted free of any obstructions in its field of view (hemisphere with unobstructed horizon). If a mast in the instrument's field of view cannot be avoided it must be oriented towards the near pole (north in the northern hemisphere), in order to minimise the impact on the instrument's readings. A full horizon view shall be photographically documented from nearby the sensor's location.

It must be noted that the irradiation sensor, regardless its type, requires regular maintenance in the form of cleaning from dust and debris. Typically a monthly schedule is adequate, but this may depend on local conditions. Safe access is, therefore, required.

For practical reasons the temperature/rel. humidity sensors within their radiation shield (with fan aspirator) shall be mounted nearby the Pyranometer. However, a location in a shaded spot on the building's side toward the near pole (north in the northern hemisphere) is ideal.

The air pressure and CO_2 sensors may be integrated in the data sampling/radio transmitter electronics housing, provided, that the enclosure is adequately ventilated to the outside.

Indoor Sensors

Placement of indoor air condition sensors shall be chosen clear of direct sun light at any time of the year, if possible at half room height / 1.10 m from the floor, on an internal wall. A proven location is by the light switches next to the door. In a room oriented towards the far pole (south in the northern hemisphere) this height may, however, be too low to exclude solar exposition in the winter and a greater height is advised in such cases (e.g. 1.8 m. The altitude of the sun at summer solstice can be estimated as 90°-Latitude+23.5° at winter solstice as 90°-Latitude-23.5°, neglecting atmospheric refraction). In highly insulated buildings temperature stratification at times without solar energy input is known to be very low (< 0.5 K over the entire height of a normal room), hence height is not overly critical. A careful documentation of the location, with photographic evidence including a yardstick to indicate the height above the finished floor level, is required for each sensor.

Meters

In most cases meters are provided and owned by the utility for billing purposes. The building design shall as far as possible anticipate the subsequent monitoring for performance verification and place the meters at the balancing boundary whenever possible. If any meters also measure meaningful amounts of energy that is used outside the thermal envelope, sub meters must be fitted to establish the respective amounts. This holds in particular for electricity meters that also measure energy for e.g. vehicle charging or powerful outdoor / garage lighting. Sub-metering can be dispensed with where the energy use outside the thermal envelope is less than 1 % of the total. A heat pump shall always be fitted with a sub-meter for *real power*(high inductive loads from the compressor motor) for the electricity input to the *heat pump system*, comprising the compressor, controls, auxiliary pumps and fans as well as a heat meter for the output.

DATA EVALUATION

CONTINUAL EVALUATION OF INDOOR ENVIRONMENT AND ENERGY USE

During the data acquisition phase, that lasts for one year or longer, data is nevertheless useful for continual evaluation of the indoor environment and metered energy. The outPHit monitoring platform provides tools to visualise the data and automatically performs a first statistical analysis. This includes the identification of minimum and maximum values, quartiles, median, arithmetic mean and standard deviation. Moreover results are binned to illustrate the frequency distribution.

A very fast and intuitive check is possible based on this data. The following examples are taken from the database and illustrate the procedure and potential, based on an exemplary data set from one bedroom in a demonstration project before retrofit.

There seems to be no overheating in the summer. As the winter comes it is getting quite cold. CO_2 concentration is low, as windows are probably open for long periods of time, with the winter approaching, they rise as the window ventilation is reduced. Relative humidity is largely unremarkable.

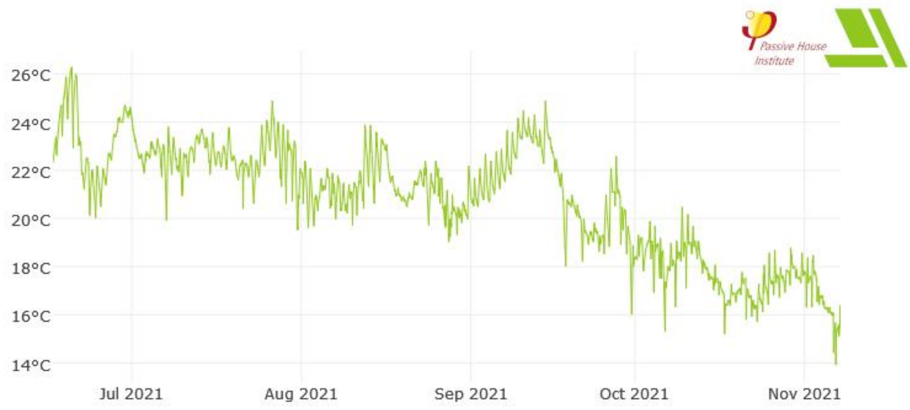


Figure 2: Lines plot of the room temperature over time

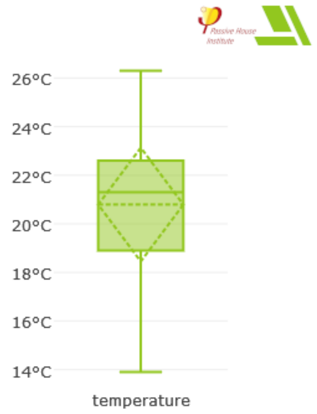


Figure 3: Boxplot of quartiles and min/max of the temperature data (mean and standard deviation added as dashed diamond)

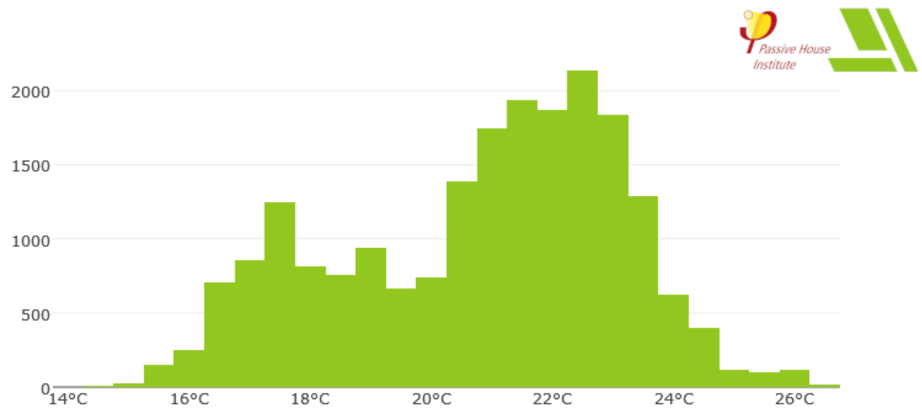


Figure 4: Histogram of the temperature readings in 0.5K bins

Threshold	Hours	Fraction %
<15	3	0.04%
<16	36	0.41%
<17	268	3.06%
<18	603	6.88%
<19	866	9.89%
<20	1111	12.69%
>25	46	0.53%
>26	6	0.07%
>27	0	0.0%
>28	0	0.0%
>29	0	0.0%
>30	0	0.0%

Figure 5: Cumulated times and fraction for temperatures beyond the given thresholds

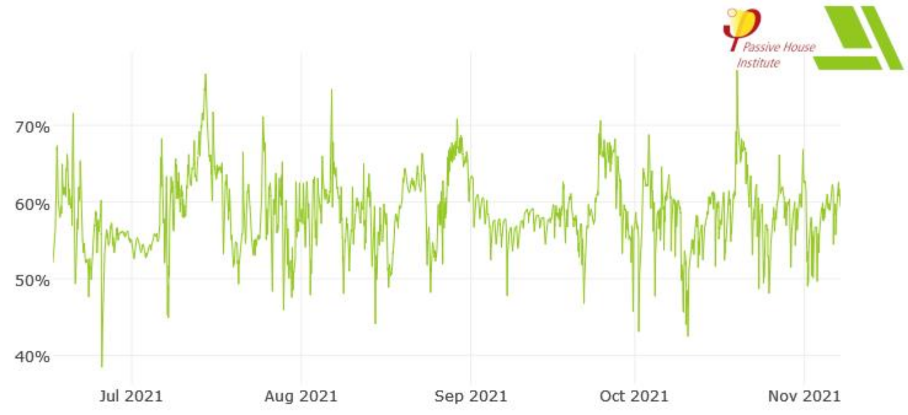


Figure 6: Lines plot of the room relative humidity over time

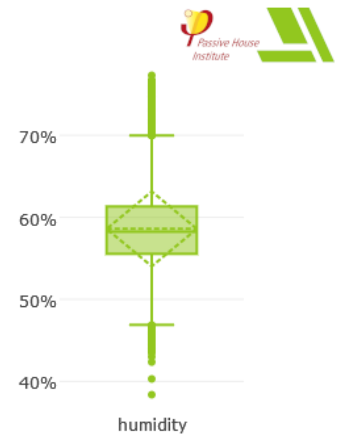


Figure 7: Boxplot of quartiles and min/max of the humidity data (mean and standard deviation added as dashed diamond)

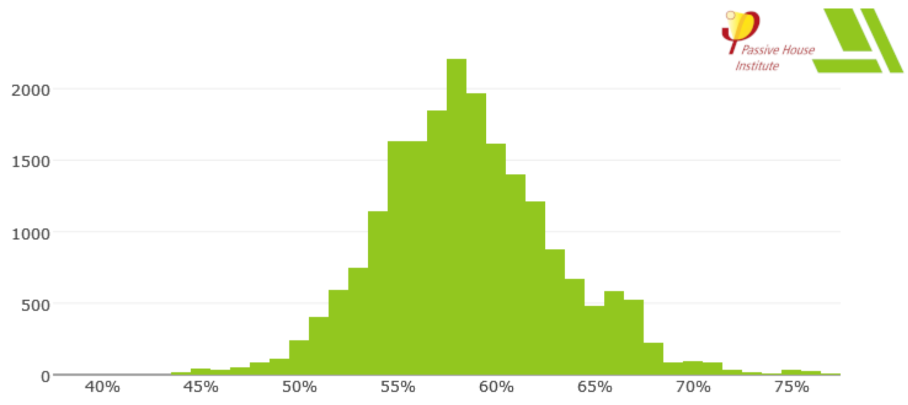


Figure 8: Histogram of the humidity readings in 1% bins

Threshold	Hours	Fraction %
<5	0	0.0%
<10	0	0.0%
<15	0	0.0%
<20	0	0.0%
<25	0	0.0%
<30	0	0.0%
>70	41	0.47%
>75	7	0.08%
>80	0	0.0%
>85	0	0.0%
>90	0	0.0%
>95	0	0.0%

Figure 9: Cumulated times and fraction for humidity beyond the given thresholds

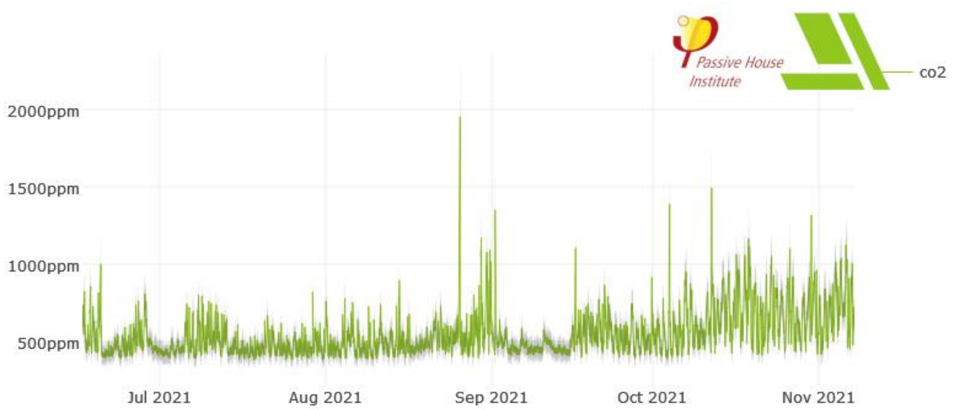


Figure 10: Lines plot of the room air CO_2 concentration over time

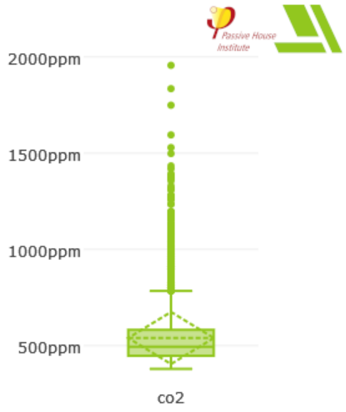


Figure 11: Boxplot of quartiles and min/max of the CO_2 concentration data (mean and standard deviation added as dashed diamond)

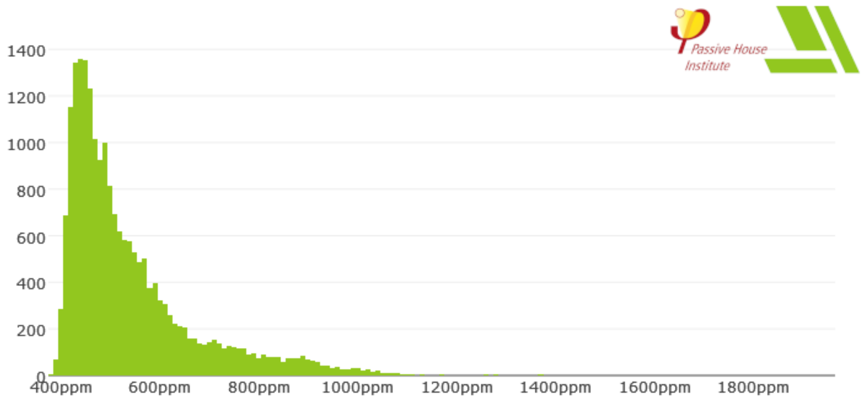


Figure 12: Histogram of the CO_2 concentration readings in 10 ppm bins

Threshold	Hours	Fraction %
>1500	1	0.01%
>1600	1	0.01%
>1700	1	0.01%
>1800	0	0.0%
>1900	0	0.0%
>2000	0	0.0%

Figure 13: Cumulated times and fraction for humidity beyond the given thresholds

QUANTITATIVE EVALUATION OF INDOOR ENVIRONMENT AND ENERGY USE

All available data is converted into monthly representations and serves to automatically update the energy balance calculations (by [PHPP] methods) with measured boundary conditions for weather and usage. The boundary conditions data set is handed to the calculation engine and results are returned in the form of another data set, for display, documentation and further use in the database. This data set also comprises information on the winter, summer and transitional periods that are used in the scope of the living quality assessment.

Weather data

Short wave solar radiation is measured as global horizontal radiation and can be handled with a sky model by [Perez/Ineichen] with regard to air pressure as a correction for air mass as well as considering air temperature and air relative humidity. The procedure follows a proven implementation in [pv_lib] and results are aggregated into monthly integrals of global irradiation on the vertical plane in the cardinal directions in addition to the measured value on the horizontal plane.

Down welling long wave radiation is estimated from the dew point of the air and considered in the form of the monthly mean sky temperature. Air temperature and relative humidity are considered as monthly mean values respectively.

Ideally, the outdoor CO_2 concentration is used as a summand in fine temporal grain for IAQ assessment in order to determine the concentration increase in interior spaces with regard to the outdoor concentration. As the latter is subject to considerable temporal variations, particularly in urban areas, it is valuable to also have the outdoor concentration measured. However, this makes sense only in cases where very high quality sensors are used, with a practical measuring uncertainty well below 50 ppm.Inexpensive sensors do not provide this level of accuracy, but auto-calibrate to the lowest observed values over a week, thus indirectly providing a reference to the outdoor value. Nonetheless, any short-term (diurnal) fluctuations are lost. Given the cost constraints that apply to the suggested monitoring approach this is considered tolerable, however.

Room conditions

A building object in the data base is subdivided into zones (e.g. flats) and rooms within these zones. Each room is characterised by its area and can be assigned a number of sensors.

Mean indoor conditions for the energy assessment of the building are derived as area-weighted means (TFA) of the room/zone values, both for temperature and relative humidity.

Internal Heat Gains

An estimate of the internal heat gains prevailing in the evaluation period is derived from the metered electricity consumption and estimated occupancy, considering

PV generation and the amount of energy delivered to the grid (exported from the balancing boundary). Deducted is any noteworthy consumption outside thermal envelope, particularly electric vehicle charging, underground parking lights/ventilation, external lighting in general as well as estimates for evaporation and drain losses.

EVALUATION CRITERIA

Uncertainties in Energy Balance Calculations

An evaluation of uncertainties involved in energy balancing for buildings has been documented in [Johnston e.a. 2020]. Based on that study an abbreviated and adapted approach is given in the following section.

Uncertainties in the determination of construction parameters

Any calculation can only be as accurate as the respective input data.

It is in the nature of buildings and construction that deviations from the design data (e.g. effective insulation thickness, thermal conductivity) can be regularly observed. Such deviations result, by uncertainty propagation, in a limited accuracy of the calculated heating energy demand of a building. The magnitude of the resulting uncertainty shall be estimated in the following discussion.

- Deviations in insulation thickness and thermal conductivity

The effective insulation thickness in a building component can vary by up to 10 mm due to construction tolerances, partially compressed insulation, deviations in the spacing of fixtures/dowelling; the nominal values for the thermal conductivity of officially approved insulation materials are, as a rule, considerably higher than the actual value and only in rare individual cases a deviation in the opposite direction is possible (e.g. caused by soaking). A typical uncertainty on the parameters of the insulation can thus be estimated by a variation in effective insulation thickness of 15 mm, which will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 0.7 kWh/(m²a).

- Deviations in operation of MVHR systems

The effective heat recovery rate in the field can be affected by air leakage, disbalance, condensation and other effects. A typical uncertainty on the parameters of the MVHR can be estimated by a variation of the effective heat recovery rate of 5 %, which will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 1.2 kWh/(m²a).

- Measuring uncertainty of the airtightness test

The leakage flow as well as the reference volume (or area) affect the accuracy of the n_{50}-value. Under practical constraints of the test (e.g. influence of wind) and building preparation both can only be determined with limited accuracy. A typical uncertainty on the parameter airtightness can be estimated by a variation of the n_{50} value of 0.05 h^{-1}, which will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 0.24 kWh/(m²a).

- Deviations in the thermal properties of windows

U-Values of windows can be determined with limited accuracy even when using the DIN EN 10077 methods. The effective glazing U-value is affected by variations in the noble gas fill concentration; dimensions of all the window components are subject to tolerances, particularly the distance from the glazing edge of spacer and edge seal. A typical uncertainty on the window parameters can be estimated by a variation of the glazing U-value of 0.05 W/(m²K) and 0.02 W/(m²K) for the frame, and 0.005 W/(mK) for the linear thermal bridge effects, which will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 0.6 kWh/(m²a).

The above items define the construction parameters of a Passive House building with regard to the annual space heating demand to 90 to 95 %. The impact of further effects is not very large (e.g. the absorption coefficient of external surfaces). The major effects discussed above are independent, hence the total effect can be lumped together with a quadratic uncertainty propagation, where x is the parameter under consideration and Δx the respective standard deviation:

$$\Delta Q_{h,tot} = \left(\Sigma \left(\frac{\delta Qh}{\delta xi} \Delta xi \right)^2 \right)^{1/2}$$

Using the respective values derived in the above discussion yields a propagated uncertainty of ±1.5 kWh/(m²a) for about 90 % of the building-related parameters.

For any calculation of the annual space heating demand, therefore, a total uncertainty of about ±1.6 kWh/(m²a) must be considered, due to inherent uncertainties in a building's construction parameters. This refers to any calculation, regardless how sophisticated and physically accurate the model might be.

Uncertainties in the determination of usage parameters

The impact of user behaviour and usage in general on the measured space heating demand is very important. Hence, the most relevant parameters reflecting the usage need to be measured if a comparison of measured vs. projected consumption is desired.

In order to estimate the uncertainty margin for usage parameters three quantities matter in particular:

- The mean room temperature

The propagated uncertainty for an uncertainty in the mean room temperature of ±0.3 K will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 4 % or 0.6 kWh/(m²a).

> Measuring this quantity with high grade sensors of lower measuring uncertainty than ±0.3 K may reduce this contribution. With the ±0.2 K sensor specification it is suggested to adjust the total uncertainty from this factor to 0.5 kWh/(m²a) for the outPHit verified performance scheme.

- The effective air change rate

It has been observed in intensely monitored buildings that in most cases windows are opened in the main heating season only occasionally and for short times. Typical effective additional air change rates (daily average) from windows and doors have been found ranging from 0.003 h^{-1} and 0.09 h^{-1} (with occasional deviations). In most cases this suggests to neglect the effect. The uncertainty in the usage-related air change rate can be estimated as ±0.012 h^{-1} which will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 1 kWh/(m²a).

> Measuring the added air change rate by recording and evaluating all window opening events involves a very high number of window contacts -which are notorious to fail- and the related monitoring equipment. The evaluation is also not easy and almost fails entirely as soon as a single window's status is not accurately logged. It is hence considered impractical to regularly measure the effective air change rate in the scope of a simplified monitoring approach. Here lies the most impactful uncertainty on the overall result and grossly unusual user behaviour may cause significant differences in measured vs. projected energy consumption. Hence, this contribution cannot be reduced and even larger amounts must be kept in mind as a possibility when evaluating monitoring results.

- The internal heat gains

Monitoring results from a large number of German Passive House buildings point to effective internal heat gains of 2 W/m² (±0.3). The figure represents the balance of positive and negative contributions. The remaining uncertainty of ±0.3 W/m² will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 1.3 kWh/(m²a).

> Primarily, the total amount of IHG can be verified for the individual case using the actual number of users and the electrical energy use from measured values. The uncertainty in internal heat gains may be also somewhat reduced, however, this effect is limited due to the unknown utilisation factor for electrical energy (e.g. drain losses from dishwashers, washing machines etc. can only be estimated by empirical factors). Hence it is suggested to remain with the ±0.3 W/m² or 1.3 kWh/(m²a) for the outPHit Verified Performance scheme.

The three main influence factors discussed above account for about 70 % of all usage-related uncertainties. If it is accepted to consider them largely independent the total uncertainty can be lumped together with a quadratic uncertainty propagation again:

$$\Delta Q_{h,tot} = \left(\Sigma \left(\frac{\delta Qh}{\delta xi} \Delta xi \right)^2 \right)^{1/2}$$

Using the respective values derived in the above discussion yields a propagated uncertainty of ±1.7 kWh/(m²a) for about 70 % of the building-related parameters.

For the calculation of the annual space heating demand, therefore, a total uncertainty of about ±2.5 kWh/(m²a) must be considered, due to uncertainties in a building's usage parameters. The figure can be reduced to about±2.4 kWh/(m²a) if the above improvements for the outPHit Verified Performance scheme discussed above are factored in.

Uncertainties in weather data

With a radiation shield outdoor air temperature can be measured with a high grade sensor to an uncertainty of ±0.15 K and good instruments permit measuring global horizontal solar radiation to ±5 %. This will yield an impact on the space heating demand of a typical Passive House building in the magnitude of 4.5 % or 0.7 kWh/(m²a).

Combined uncertainty from construction parameters, usage parameters and weather data uncertainty

The three categories of uncertainty discussed above, namely construction parameters, usage parameters and weather data uncertainty can regarded as independent. Therefore, the total uncertainty can be lumped together with a quadratic uncertainty propagation and yields a result of ±3 kWh/(m²a).

> This value can be confirmed for the outPHit Verified Performance scheme as only slight improvements over the already ambitious assumptions of the original investigation are practical.

Even with an accurate energy balance model, careful inputs and correct usage of the model the available accuracy of input data does not permit a lower uncertainty in the results, regardless how sophisticated the method is (e.g. dynamic building simulation with high spatial and temporal resolution).

The remaining uncertainty amounts to a low absolute value that does not materially change with regard to a building's energy efficiency standard. However, with decreasing energy demand the proportion of the uncertainty in the energy consumption figures naturally increases. This, on the other hand, is still of limited significance, given the very low figures e.g. in a Passive House building.

Particularly for the deep retrofit context in the outPHit project measured and calculated values pre- and post-refurbishment will still be amply accurate to establish the successful implementation of the chosen measures and the resulting energy savings.

For different energy efficiency standards the absolute uncertainty of ±3 kWh/(m²a) implies the relative uncertainty according to the table. The outPHit demonstration projects are expected to meet the [EnerPHit] heating demand criterion of 25 kWh/(m²a) with a relative uncertainty of 12 %.

Standard	Useful space heating demand [kWh/(m²a)]	Relative uncertainty [%]
EnerPHit (small bldg., component reqirements)	45	6.6
EnerPHit (large bldg., heating demand)	25	12
Low Energy Building	30	10
Passive House (limit)	15	20
Passive House (++)	10	30

Table 5: Relative uncertainty values of monitoring result evaluation for different energy efficiency standards

Conclusion with regard to the development of certification criteria

Despite good grade sensors, determination of inputs is subject to uncertainties. For highly energy efficient buildings a comparatively high relative uncertainty results from the largely absolute nature of the uncertainties involved: Matching the calculated results will never be possible with less than about ±1.6 kWh/(m²a) that are inherent to construction properties uncertainties. Additional uncertainty results from usage parameters, the amount depends partially on the grade of sensors. User behaviour in terms of additional air change via windows is, and remains, the most significant unknown. To measure it a complete suite of sensors for all openings were required that also distinguish tilt vs turn as well as the turn angle, and each sensor would present a single point of failure for the entire effort. A serious approach would multiply the cost for sensors as well as the complexity of the evaluation. Hence it is considered impractical, but also dispensable, in the vast majority of cases within the scope of the outPHit verified performance programme.

The PHPP monitoring data evaluation yields a plausible range for results, taking measuring uncertainties into consideration (as uncertainty limits). Located within the band lies the range of ±3 kWh/(m²a) derived above. It might be a useful and simple criterion, provided, the outPHit specifications for sensor measuring uncertainty are met.

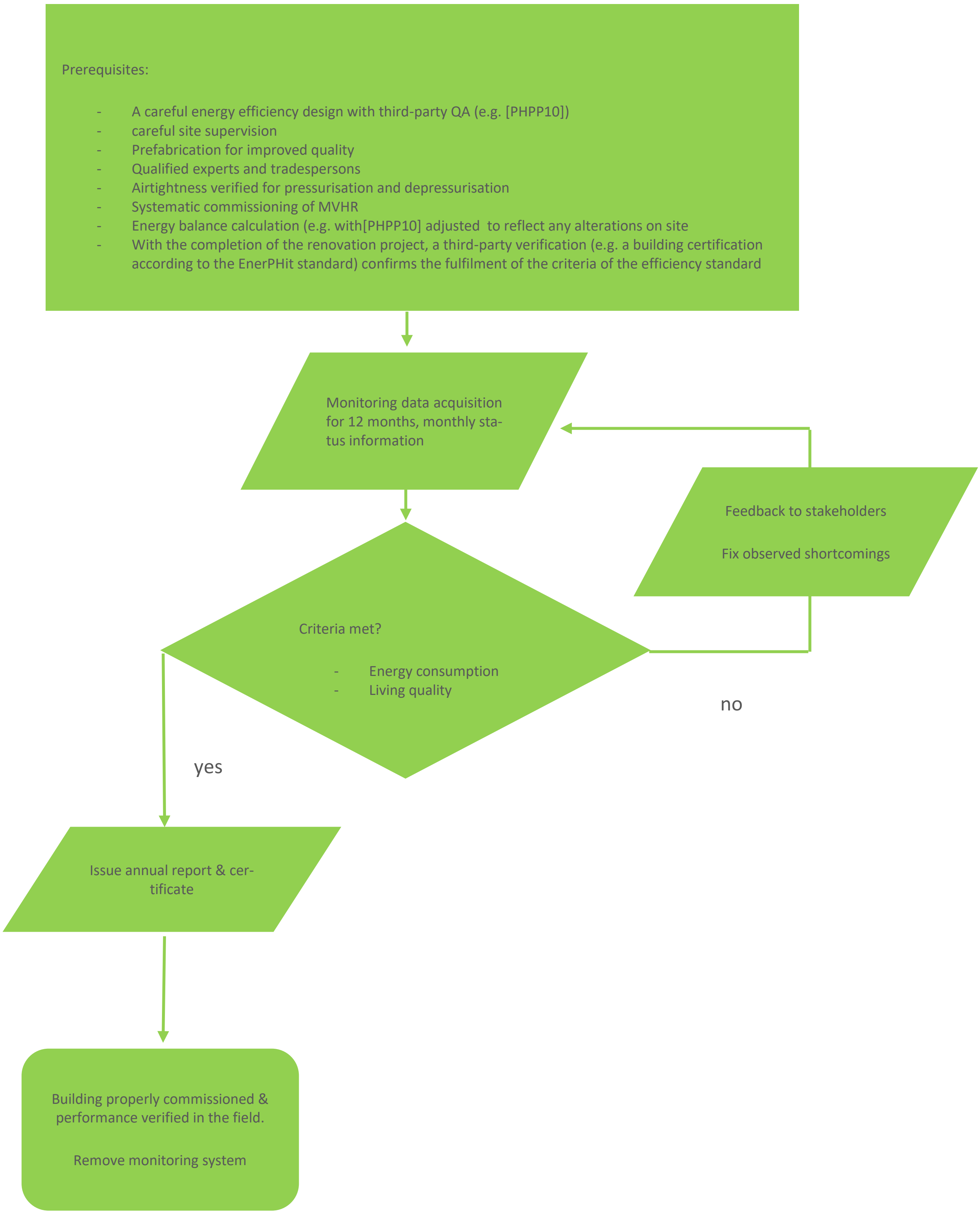
If household electricity consumption exceeds a certain limit (e.g. 15 kWh/(m²a)), feedback to the building users shall be triggered and guidance on efficient use of electricity be given.

While monthly balance calculations are valuable and can support informed performance optimisation, they may contain some bias due to seasonal capacity effects (e.g. sensible and latent heat absorbed into or released from the building structure), slightly distorting the monthly values in the spring and autumn. Therefore, it might be considered to base any certification only on the annual values. This way, the vast majority of capacitive effects can be assumed to cancel each other.

First-year effects, such as drying of concrete, screed and other building materials can have a considerable impact. Systematic evaluation should, therefore, use the first year for error detection and building services optimisation, while only in the second year a robust evaluation of energy performance can be made.

For refurbishment projects the old condition of the building also presents a useful reference. If billing information or meter readings are available for all relevant energy carriers they are the best possible source. In other cases, a variant of the energy balance calculation with PHPP may be performed for the unrefurbished condition, taking a reduction factor for partial heating/reduced average indoor temperatures into account. With regard to this reference a global reduction in space heating demand of 75 % should be achieved.

Process schematic



LIVING QUALITY ASSESSMENT

The living quality is systematically assessed following a procedure outlined in [Rojas-Kopeinig] and uses an integration of times beyond a target threshold relative to a critical limit value. In this way different parameters (temperature, relative humidity, CO_2-concentration) can be evaluated separately but nonetheless be combined into a single characteristic value. The method can be applied for every room, and is suited to area-weighted averaging for zones or entire buildings. It can be performed for every season. A time weighted average of the seasonal results, representative of the entire year is also possible. Further detail is provided in *D6.11 : Report on living quality indicators before and after retrofit*.

DOCUMENTATION

The monitoring platform generates a standardised report skeleton, that documents the central measurement results, based on the measured values, the energy use assessment and verdict with regard to the certification criteria (cf *D6.7 : Certification Criteria for "verified building performance"*), and the living quality assessment. Plots and tables make it easy to understand and the guiding principle is to reduce any text to the required minimum. It can be further edited manually to reflect specific conditions.

If consent is given, the evaluation results are also displayed as part of the publicly accessible on-line documentation of the outPHit case study projects at

www.outphit.eu .

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APPENDIX A

REQUIRED SENSORS ESTIMATION EXAMPLE

Example

Type of Node	Quantity	Description
Weather	**1**	On neighbour's roof to escape shading
Room air conditions		
	11	classrooms
	3	Circulation and hall
	1	canteen
	1	kitchen
	1	gym
	1	Changing room
	1	Plant room
Total Room air conditions	19	
Meters		

	1	Electricity main
	1	El. Heat pump sub
	1	El. MVHR sub
	1	El. Exterior Lighting etc sub
	1	Heat Heat pump
	1	Cold Heat pump
Total Meters	6	

APPENDIX A

REQUIRED SENSORS ESTIMATION PRO-FORMA

Type of Node	Quantity	Description
Weather Node	**1**	
Room Air Conditions Node		
Total Room Air Conditions Nodes		
Meter Node		

Total Meters Nodes		

APPENDIX B

ON-SITE SETUP CHECK LIST AND DOCUMENTATION

1. Complete floor plans with sensor and meter locations.
2. Complete list of sensor types and meter types, datasheets with full specifications.
3. All sensors documented in situ with photographs, with yardstick and referenced to floor plan.
4. All meters documented in situ with photographs, pulse pick up attached and pulse counter fitted.
5. Complete and true list of all sensor types with LoRa ID and installation location in digital format.
6. Complete and true list of all meter serial numbers for positive identification.
7. On-line evaluation of functionality while staff still on site to troubleshoot glitches. Make appointment well ahead of time.