Fan pressurization method for measuring air leakage in churches – wind and stack induced uncertainties

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ABSTRACT

The air leakage of the building envelope of ancient churches and other historical and monumental buildings has impact on energy consumption, thermal comfort, humidity and indoor surface soiling. To measure the air leakage in such large and naturally ventilated single-zone buildings is however challenging, especially due to wind and buoyancy (stack) induced disturbances. This study describes experiences in this regard, attained at field tests where the fan pressurization technique ("Blower door") was employed. Reference is made to the European test standard EN 13829. Also results of wind-tunnel tests are utilized. It is shown that both buoyancy and wind at commonly occurring conditions can cause significant uncertainty in fan pressurization tests, and that some of the directions in the standard might need to be strengthened or amended. While the uncertainty in measured air leakage rate at the standard (high) pressure of 50 Pa may be small, the predictions of the air leakage rate occurring at realistically (low) indoor-outdoor pressures tend to suffer from significant uncertainty. That uncertainty is then conveyed to later utilizations of the test results, e.g. building energy modeling and prediction. It is also shown that the wind induced pressure at buildings like churches extends a considerable way out into the surroundings of the building; in the order of two times the building height. This has particular importance when choosing a reference point for outdoor pressure measurement.

Keywords

Air infiltration, Building tightness, Fan pressurization test, Churches, Wind, Stack effect, Ventilation

1. Introduction

The air leakage of the building envelope of ancient churches and other historical and monumental buildings affects their energy consumption when heating is required. These buildings tend to be leaky, and the sealing possibilities are often limited by esthetical and preservation considerations. Air infiltration also affects humidity in indoor air and building construction, and it may cause uncomfortable draughts. It also needs to be considered in view of possible HVAC installations. Further, air infiltration affects the indoor concentration of airborne particles, whether their major source is from indoors or outdoors; thus influencing the soiling rate of indoor surfaces.

By far the most common technique to measure the air leakage of building envelopes is the fan pressurization method (often called "blower door" method). This method implies measuring the amount of fan induced airflow that is needed to pressurize the building to various indoor-outdoor pressure differences. Leakier buildings will require higher airflow rates to pressurize the building to a certain level, whereas tighter buildings will require lower flow rates. Blower door technology was first used in Sweden around 1977 as a window mounted fan (as reported by [4]) and to test the tightness of building envelopes ([1]). Today, standardized test procedures for performing fan pressurization measurements are described in e.g. the European standard EN 13829 [2], which is implemented by most European countries, and which will be referred to repeatedly in this paper. The EN 13829 standard implies the commonly used multi-point test procedure where "air moving equipment" is controlled to induce a series of target indoor-outdoor pressure differences, Δp. The "air moving equipment" is usually a so-called blower door fan, temporarily sealed into an exterior doorway by using a purpose-made door-panel system. The blower door equipment includes an air flow meter, measuring the induced air flow rates, q, needed to achieve the target pressure differences. The pairs of Δp and q data are then regressed in a least-squares manner to yield a power-law equation for their relation:

$$q = C_L \cdot \Delta p^n \qquad (1)$$

where the air flow coefficient, C_L, and the flow exponent, n, signify the leakage characteristics of the building. Empirical studies (e.g. by [6]) have suggested this widely used expression to be suitable. Once these coefficients have been determined, the most common quantities to express the air leakage (also stated in the EN 13829 standard) can be calculated:

- Air leakage rate at a reference pressure difference, usually 50 Pa (q_{50}),
- Air change rate at the reference pressure difference: $ACH_{50}=q_{50}$ divided by the internal building volume,
- Air permeability = Air leakage rate at the reference pressure difference divided by the building envelope area.

However, such a high pressure difference as 50 Pa hardly ever occurs across building envelopes in practice; in naturally ventilated buildings it seldom reaches above 10 Pa [3]. It is therefore common to express the air leakage as an estimated air leakage rate at a more realistically occurring pressure difference, commonly at 4 Pa (q_4). Another often used result

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quantity is the Effective Leakage Area, *ELA,* which also is related to a more realistic pressure reference, typically $\Delta p_{ref} = 4$ Pa. The *ELA* is then given by:

$$ELA = \sqrt{\frac{\rho}{2}} \cdot C_L \cdot \Delta p_{ref}^{\ (n-0.5)} \qquad (2)$$

In the case of churches and similar naturally ventilated, large "single-volume" buildings, pressurization tests may however evoke particular concerns. Substantial fan power may be needed and the measurements of indoor-outdoor pressure difference can be complicated in these often wind-exposed buildings, where also stack effect may be considerable. The present study deals with these issues in conjunction with field measurement results, as well as wind-tunnel tests of pressure-affected areas around a church model.

2. Methods

Fan pressurization tests were performed at an 1850's stone church (Figure 1), in Hamrånge, central Sweden.

Figure 1 Hamrånge church.

The interior volume of the church is 7700 m^3 and its outer dimensions L×W×H=63×18.5×17.2 m, with a 45 m tower. It is a hall church with 1.3 m thick stone walls, double glazing (weatherstripped) and a wooden floor with a crawl space underneath. The whole church, including the crawl space, is naturally ventilated, without any flues. The inner walls and the ceiling are plastered. Besides three larger porches, the church has a smaller, weatherstripped door where blower door equipment could be installed (Figure 2; two 2200-Fans with DM-2A manometers, Retrotec Energy Innovations Ltd.). Additional more precise measurements of the indoor-outdoor pressure difference were performed using three separate manometers (FCO44, 0-60 Pa, Furness Controls Ltd, East Sussex, UK). Room air temperatures were measured at different heights in the church using gold-sputtered NTC thermistors (Ø0.47 mm, 4 mm long). Outdoor air temperature, humidity, wind speed and wind direction was recorded at a local weather station (Vaisala WXT520), situated 1 km from the church.

Figure 2 Blower door set-up.

The church is situated on a 10 m high hill with wooded slopes (visible in Figure 1) facing westwards direction (sector South-East to North). Beyond the wooded slopes there are mainly open fields in that direction. Eastwards (between North and South-East), about 200 m from the church, is the edge of the small village of Bergby, consisting of low-rise buildings (one- to three-storey) and some wooded areas.

Figure 3 Church model in wind tunnel.

A model of the church in scale 1:200 was placed in a wind tunnel (University of Gävle, Figure 3) for the purpose of studying the wind load on the building, but also to explore the wind affected ground area around it. For the latter purpose the church model was placed on a plate provided with 400 pressure taps arranged in a quadratic pattern at 37 mm spacing. Floor roughness cubes were placed upstream in the wind tunnel to simulate the atmospheric boundary layer over a flat, open terrain.

3. Results

3.1 Stack effect considerations

In an initial test with no fan pressurization, the Indoor-Outdoor pressure difference was measured for 24 hours (over two days in October) across the middle of both long sides of Hamrånge church, with pressure tubes ending on the outside of porch keyholes at 1.6 m over the floor level. A period of calm weather (wind speed < 1 m/s) was identified during night time, and the measured simultaneous Indoor-Outdoor temperature, ΔT, at different heights of the church is depicted in Figure 4. The figure indicates that ΔT is rather homogeneous in the upper part of the church, while a slight temperature gradient (stratification) exists below about 5 m height. Such stratification occurs due to cool air downdraught and infiltration through walls and floor, while heated air rises. The measured Indoor-Outdoor pressure difference, Δp, at keyhole-height was on this occasion -1.5 Pa (±0.1 Pa) on both sides of the church. In the absence of wind, this pressure difference ought to be caused by buoyancy (stack effect). The stack induced pressure difference, Δp_s, across the building envelope will vary with height, and this variation can be estimated by letting all measured ΔTs represent a layer of air, Δh, that extends between the midpoints of the adjacent temperature measuring points. The accumulated stack-induced pressure difference at a certain height, $\Delta p_s(h)$, can then be estimated as:

$$\Delta p_S(h) = \sum_{height=0}^{h} \left(\rho \cdot \frac{\Delta T}{T} \cdot g \cdot \Delta h \right) \qquad (3)$$

where h=height above the floor [m], ρ=air density (mean of indoor and outdoor) [kg/m^3], ΔT is the indoor-outdoor air temperature difference [°C] at the height h, T is the air temperature in Kelvin, and g is the gravitational constant [m/s^2]. With the ΔTs in Figure 4 this equation yields a pressure difference at full ceiling height $\Delta p_s(H)$ = 9.48 Pa, representing the total magnitude of the stack-induced pressure. In the case of negligible wind effects, the actually occurring Δp at a certain height can be obtained by adding the pressure difference at floor level, Δp_{floor}, i.e.

$$\Delta p(h) = \Delta p_{floor} + \Delta p_S(h) \qquad (4)$$

In the present case, Δp_{floor} can be estimated by utilizing the measured Δp at keyhole-level and an interpolated Δp_s at the same height, yielding: $\Delta p_{floor} = \Delta p(1.6) - \Delta p_s(1.6) = -1.5 - 1.05 = -2.55$ Pa. Figure 5 shows the resulting pressure variation with height, $\Delta p(h)$ (circular symbols). The curve is slightly bent (hardly discernible) due to the temperature gradient. Very close to that curve is another black, ,straight curve, which is obtained in a similar, but simpler way: The temperature variation with height is neglected and instead a homogeneous indoor temperature is assumed, being represented by the temperature measured closest to mid-ceiling height. With this method, $\Delta p_s(H)$ becomes 9.61 Pa, differing only 1 % from the previous 9.48 Pa. The similarity between the curves indicates that vertical temperature variations of the magnitude in Figure 4 are more or less negligible in assessing stack-induced pressures. By interpolation, the height where Δp=0, i.e. the so called Neutral Plane Level, *NPL*, can be estimated to be at 3.81 m above the floor. This is at 27.8 % of the total ceiling height (H=13.7 m), i.e. at a relatively low level. (The simpler "homogenous temperature" method yields 27.4 %.)

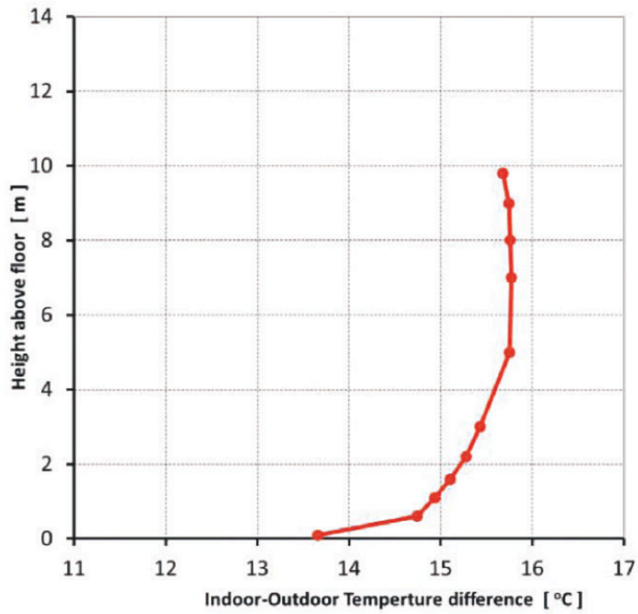

Figure 4 Vertical temperature variation.

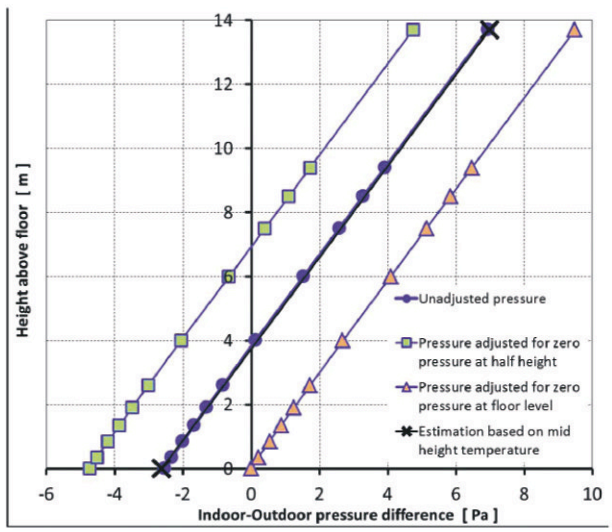

Figure 5 Vertical pressure variation.

When performing blower door measurements, the indoor-outdoor pressure difference is usually measured at floor level, and this is also what is assumed in the EN 13829 standard. That standard also involves measuring the "zero-flow" pressure difference, i.e. at no fan pressurization. That pressure difference should then be used as an offset value, which should be subtracted from all pressurization data before further analysis of them. In the present situation, depicted in Figures 4 and 5, this would mean subtracting Δp_{floor}=-2.55 Pa from all pressure data, resulting in the right pressure curve in Figure 5 (triangular symbols). It would seem that it is then only at floor level that Δp is zero; higher up there is a positive indoor pressure, and on average there is an overpressure of about $\Delta p_s(H)/2$ = 9.48/2 =4.74 Pa. A pressurization test with leakage calculations according to EN 13829 would in this case thus imply using pressure difference data that differ by almost 5 Pa from the actual data. Instead, if measurements and calculations of the stack induced pressure distribution have been performed, as above, it might seem more relevant to adjust the pressurization data so that the *height-averaged* Δp_s is zero when no artificial pressurization is induced. Since Δp_s varies practically linearly with height, as shown in Figure 5, this means adjusting the pressure values so that Δp_s=0 at half ceiling height, H/2. The pressure adjustment to achieve this can be obtained by interpolating the present data, yielding a pressure subtraction of +2.19 Pa. Applying this to the unadjusted pressure curve in Figure 5 results in the curve to the left (square symbols). That curve represents the closest to overall zero-Δp that we can get in the present situation, and appears to be the best representation of the baseline level to use in subsequent leakage calculations.

The previous reasoning points to the uncertainty involved in the choice of zero-Δp representation; in the present case it appears well motivated to subtract a little more than 2 Pa from measurement data rather than adding about 2 Pa, which the standard prescribes. The impact of using +2 Pa instead of -2 Pa as offset adjustment is exemplified in the following.

Figure 6 shows the results of a pressurization test performed in Hamrånge church. In this case depressurization was applied, and the maximum pressure difference achievable with the equipment available was 35 Pa. Measurement values down to about 9 Pa are included in the analysis. Besides data for unadjusted pressure, data also of adjusted pressures of -2 and +2 Pa are included in the figure. Power-law regression lines are fitted to the data (according to (1)).

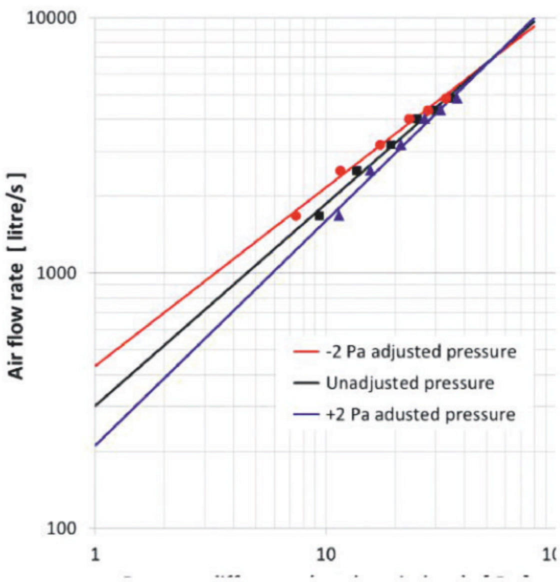

Figure 6 Result of pressurization test, with different methods to make off-set adjustment of the pressure.

The constants of the corresponding power-law equations are given in Table 1, where also interpolated flows at 50 and 4 Pa are presented. Figure 6 indicates small discrepancies between the curves at high pressure differences; at the most used reference value of 50 Pa, the interpolated flow is practically the same for all three curves. At small pressure differences, however, the differences are larger. Table 1 shows that the interpolated flows at 4 Pa, q_4, get about 26 % larger when adjusting the pressure data by -2 Pa, and 21 % smaller when adjusting them by +2 Pa. If adjusting by -2 Pa – which can be argued for as described above – instead of the standard-generated +2 Pa, q_4 becomes 60 % larger, i.e. a huge difference.

Table 1 Correlation constants and interpolated leakage flows for the cases in Figure 6.

	Power-law constant, C_L [l/s/Pa^n]	Power-law constant, n [-]	Interpolated flow at 50 Pa [L/s]	Difference to unadjusted case [%]	Interpolated flow at 4 Pa [L/s]	Difference to unadjusted case [%]
Unadjusted pressure	301	0.792	6674		903	
-2 Pa adjusted pressure	432	0.699	6668	-0.1	1139	+26.2
+2 Pa adjusted pressure	210	0.881	6604	+1.1	713	-21.0

3.2 Wind effect considerations

Figure 7 shows results of outdoor pressure measurements on the ground of the windward side of Hamrånge church. The figure shows the pressure variation over 10 min at 1-s intervals, for three different distances (0, 3 and 10 m) perpendicularly out from the middle of the façade. The median wind speed was on this occasion 5.4 m/s and the wind direction about 30° to the normal of the façade. The indoor temperature here was only about 0.6 °C higher than outdoors, i.e. the stack effect was very small. The figure indicates that the pressure is fairly similar in all three measurement positions, but that it fluctuates severely – both in short and long term – ranging between about 0 to 20 Pa. It is likely that the windward façade was exposed to wind induced pressures of a similar magnitude, and that this magnitude ought to be troublesome in view of pressurization tests.

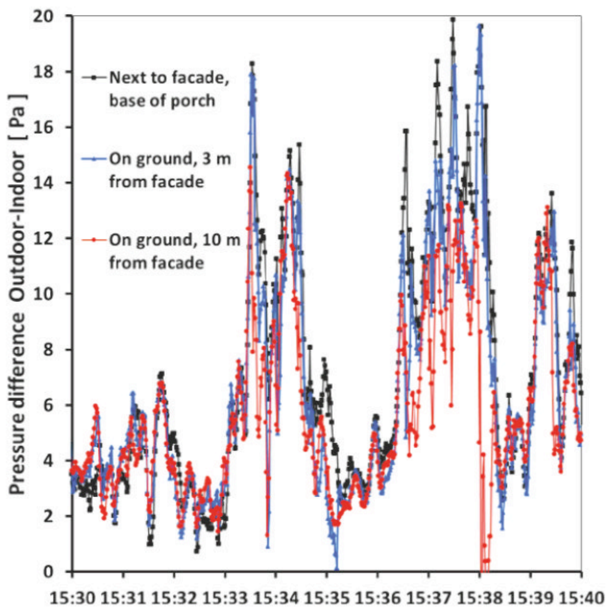

Figure 7 Outdoor-Indoor pressure variation at windward façade of church.

More information on the wind affected area around church-like buildings was attained from the wind tunnel tests. These were performed at different angles of wind attack, and Figure 8 shows results that pertain to the measurement case of Figure 7. The values on the isobar curves are local pressure coefficients, c_p = local pressure divided by the dynamic pressure at tower height. The figure indicates an overpressure on the windward side of up to c_p= +0.3, and an even greater underpressure, c_p down to -0.6, on the leeward side. It also appears that the wind affected area is fairly large; the area with absolute c_p >0.1 extends roughly 35 m out from the building, corresponding to about 2 times the building height (roof ridge). The pressure pattern also makes the findings in Figure 7 credible, i.e. that the pressure within 10 m of the middle of the façades ought to be of similar magnitude.

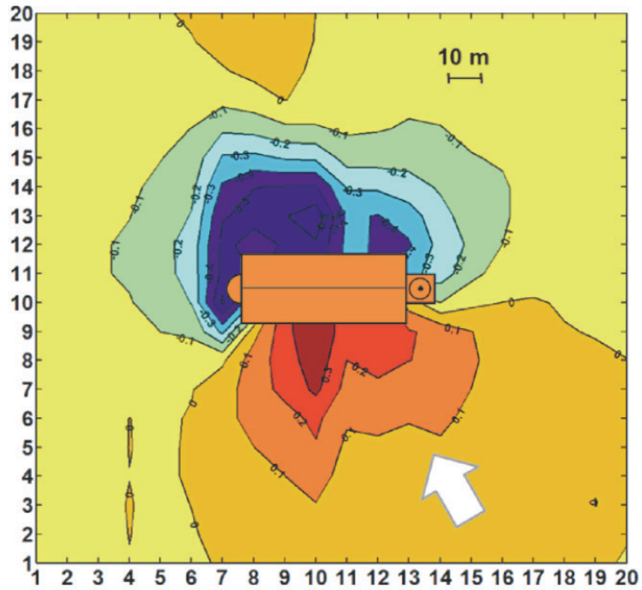

Figure 8 Isobars on ground around church model in wind tunnel. 2-D interpolation of measurements in 20×20 pressure taps. Angle of wind attack: 30° to the normal of the façade.

4. Discussion

In the first example above, a stack effect (buoyancy) induced pressure Δp_s(H) of almost 10 Pa was noted. That magnitude of Δp_s(H) appears to be common, at least in churches in the Swedish climate, and it seems to be large enough to result in significant uncertainty at fan pressurization air leakage tests in buildings. It will cause any nominal pressure difference used in the $\Delta p \leftrightarrow q$ relationship to involve a difference in Δp of 10 Pa between floor and ceiling level, which is considerable, even at the standard pressure level of 50 Pa. It was shown that only the doubt that the stack effect caused in how to make offset adjustment of the pressure data resulted in appreciable uncertainty in the low (realistic) pressure leakage rates that the test predicted. It appears that an ambiguity in just a few Pascals in what representative pressure difference, Δp, to use in a given situation results in a significant uncertainty in predicted air leakage rates at realistic climate conditions. And that uncertainty is conveyed to later utilizations of the test results, e.g. air infiltration models of different kinds. For instance, the LBL model [5] needs an estimate of *ELA* as input data, and the AIM-2 model [7 & 8] needs estimates of the power-law constants C_L and *n;* and all these factors are affected by the recognized uncertainty. The standard EN 13829 [2] states a stack effect limit of ΔT*H=500 °Cm above which it is unlikely that satisfactory pressurization tests can be performed. In the above presented case (Figure 4) it was ΔT*H≈15.6*13.7=214 °Cm, i.e. well below the limit. However, the uncertainty problems described above exist, indicating that the 500 limit might be too relaxed and needs to be strengthened. An estimation of how the stack effect pressure is distributed vertically, like in Figure 5, seems to yield additional useful information, e.g. for assessing a reasonable offset pressure to add to the subsequent pressurization test data. This estimation could be made as described above, through calculations based on simultaneous measurements of ΔT and of Δp_s at floor level.

A period of calm weather is however required, while logging of these quantities for some time might be needed.

Regarding wind effects, it seems virtually impossible to perform satisfactory pressurization tests in such conditions as in Figure 7. Not only is the magnitude of the wind induced pressure large, but it also varies substantially, with periods of up to two minutes or more. This occurred at a median air speed of 5.4 m/s. The standard EN 13829 [2] states that it is unlikely that satisfactory measurements can be performed "if the meteorological wind speed exceeds 6 m/s…". It certainly appears that a wind speed considerably lower than 6 m/s is required, at least for churches and similarly large buildings. The standard also stipulates that the zero-flow Δp should be averaged "over a period of at least 30 s", which seems to be too short a time on occasions with fluctuating wind.

Figure 8 indicated that the wind affected area around a church is fairly large, extending roughly 2×building height both windwards and leewards of the building. It is important to be aware of this at pressurization tests; it seems that the outdoor pressure reference point needs to be situated at a considerable distance from the building. The standard EN 13829 [2] says "Especially in windy conditions it is good practice to place the exterior pressure tap some distance away from the building but not close to other obstacles." Here, "some distance" is certainly vague; an indication of the approximate minimum distance would be welcome.

In the air leakage test described above, only *depressurization* was applied, which is acceptable according to the EN 13829 standard, although it recommends performing both *pressurization* and *depressurization*, if practicable. It seems that some of the uncertainties noted above can be reduced by applying both under- and overpressure; this is one of the issues that we intend to pursue in further studies.

5. Conclusions

The study indicates that both buoyancy and wind in commonly occurring conditions can cause significant uncertainty in fan pressurization tests, and that some of the directions in the EN 13829 [2] standard might need to be strengthened or amended, at least for churches and similar large single-zone buildings, particularly the standards' directions on stack effect limit, maximum wind speed, location of outdoor pressure measuring point and pressure offset procedure. Guidance on the latter issue and on buoyancy induced uncertainty can be obtained by complementary measurements of the vertical distribution of the stack effect pressure in the building. It is also shown that while the uncertainty in measured air leakage rate at the standard (high) pressure of 50 Pa may be small, the predictions of the air leakage rate occurring at realistically (low) indoor-outdoor pressures tend to suffer from significant uncertainty. That uncertainty is then conveyed to later utilizations of the test results, e.g. building energy modeling and prediction.

6. Acknowledgement

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