Reliability Demonstration of A Novel Randomized Measurement and Verification Method for Switchable Control Retrofit Using Large-scale Public Dataset

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Conventional measurement and verification (M&V) methods for whole-building energy savings estimation are both time-consuming and unreliable, especially when non-routine events occur during the M&V process. Those events are unrelated to the proposed intervention strategy but have substaintial impacts on the building energy consumption. In this study, we argue that for switchable interventions (e.g. most of the control retrofits) can benefit from random sampling where the analyst randomly decide which strategy (i.e. baseline or intervention) to implement each day. We tested the novel randomized M&V method on a large public dataset which covers multiple climate zones and types of commercial buildings. We applied a virtual chilled water supply temperature reset based on outdoor weather as a control retrofit intervention. Our study shows that the new M&V method can estimate the savings accurately much quicker than the conventional method and most importantly, the estimation results are much more robust compared to the conventional method when non-routine events are present.

# 1 Introduction

## 1.1 Background

### 1.1.1 Conventional M&V

Measurement and Verification (M&V) is the process of quantifying energy savings from energy efficiency projects by comparing actual energy consumption against a baseline, adjusting for factors like weather and occupancy. This process ensures that improvements in energy performance are accurately evaluated. In the United States, practitioners often refer to ASHRAE Guideline 14, the International Performance Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Program (FEMP) for standard guidelines ASHRAE (2014). These guidelines outline standardized methods for quantifying energy savings, whether through calibrated simulations or monitored measurements for specific equipment or systems (isolation methods) or for entire buildings (whole-building methods). In this study, we will focus on the energy savings quantified at the whole-building level where the measurements are obtained from utility bills or whole-building meters. The corresponding M&V process required by ASHRAE Guideline 14, which we refer to as the convention method in this paper. Typically, the process begins with baseline measurements taken over a year before implementing any energy-efficiency retrofit, followed by the same measurement procedure during the intervention period. After collecting two years of data, an M&V analyst fits an energy prediction model, using variables such as outdoor temperature and time (Mathieu et al. 2011) to project baseline energy consumption in the post-retrofit period. The difference between the counter-factual baseline and the measured intervention represents the energy savings. A key drawback of this method is its reliance on a two-year timeline to quantify savings, during which baseline measurements can become outdated due to changes in building performance caused by non-routine events unrelated to the intervention. This limitation reduces the feasibility of rapid M&V and complicates the quantification of estimation uncertainty, thus impacting the accuracy and timeliness of savings assessments.

### 1.1.2 Randomized M&V

To address the limitations of conventional M&V methods and the challenges posed by non-routine events, we propose a novel M&V method that adopts the randomized crossover design, a concept borrowed from medical and agricultural studies. Another improvement is that we proposed a sequential evaluation framework and defined stopping criteria to end the M&V if the target effect is detected. This is to avoid unnecessary measurement collection over the full 2-year M&V cycle. The full framework is detailed in another study with all stopping criteria outlined . In summary, this method provides M&V analysts with a randomized schedule that alternates between baseline and intervention implementation while ensuring balanced sampling across days of the week. For example, given a 10-week M&V period for 1 intervention, the balanced randomized schedule would equally sample 5 Mondays with the baseline and 5 Mondays with the intervention. The limitation of the randomized M&V is that it is only applicable to a subset of retrofit projects such as control interventions. However, for all applicable use cases, it allows analysts to detect energy savings sequentially as the study progresses meaning once the desired savings target is achieved, analysts can terminate the M&V. The key advantage of randomization, which is one of the study objectives, is that if control strategies are sampled with equal probability, the influence of non-routine events is likely to be evenly distributed between the baseline and intervention measurements. This means that the savings estimate, calculated as the difference between the two, effectively ‘cancels out’ the impact of these disturbances, leading to a more accurate and unbiased assessment of the intervention’s impact.

### 1.1.3 BDG2 dataset

The Building Genome Dataset 2 (BGD2) is an extensive open-access dataset designed to advance research and development in building energy efficiency and control strategies acting as a test-bed for modeling, simulation, and algorithm development (Miller et al. 2020). BGD2 contains over 500 buildings’ metadata and realistic operational information from across North America and Europe, making it one of the most comprehensive collections of building-related data available for scientific use. The dataset includes various commercial building types such as offices, education facilities, public, and retail buildings, and provides detailed information on their physical characteristics (e.g. enregy ratings, heating types and floor area) and hourly measurements of chilled and hot water, electricity, gas usage as well as site outdoor weather conditions.

For the purpose of this study, we only queried whole-building hourly electricity usage. All building names and precise locations were erased but the climate zone and city name were provided, which are shown in Figure 2.2 and Figure 2.3. In addition, the measurements were pre-processed by the authors with timestamp already converted to local time. We further described the data filtering process in Section 2.

## 1.2 Literature review

### 1.2.1 Measurement and verification energy-efficient measures

Most research related to M&V for whole-building approach focuses on the accuracy of baseline modeling, exploring model performance from simple regression models to more complex machine learning techniques. One study reviewed various models suitable for M&V applications as well as selected input features (Alrobaie and Krarti 2022) and another study provided a definitive methodology to apply machine learning models for M&V use cases (Gallagher et al. 2018). In addition, a few studies investigated the critical performance metrics to evaluate the developed baseline models Granderson and Price (2014) and compared a variety of models using those metrics (Granderson et al. 2016). These studies made significant contributions by emphasizing the uncertainty associated with the model-fitting process, a key factor in accurately determining energy savings. Furthermore, other researchers addressed this issue by leveraging statistical formulation and inference to improve baseline energy models Walter, Price, and Sohn (2014). However, a gap still remains in the literature regarding the rigorous quantification of uncertainties directly associated with calculated savings, for instance, accounting for the potential bias that baseline model might deteriorate (i.e. becomes ‘stale’) over an extended period of pre- and post-analysis.

### 1.2.2 Impact of non-routine events on building energy usage

A common non-routine event in energy-saving M&V projects is a change in occupancy or a significant shift in occupant behavior. These changes can greatly affect measured energy consumption in buildings and are typically unrelated to the intervention strategy. For instance, during the COVID-19 pandemic in 2020, most commercial buildings were unoccupied, leading to a noticeable drop in energy bills despite no energy-efficiency measures being implemented Kang et al. (2021). Furthermore, subsequent research has shown that hybrid working modes, allowing employees to work remotely, have persisted after the outbreak of the pandemic (Aksoy et al. 2022), adding further complexity to energy consumption patterns due to evolved occupant behaviors with higher flexibility Xie et al. (2021). One study realized the limitation of current M&V methods, which only consider adjusting for outdoor weather, is insufficient and emphasized the importance of requiring matched comparison groups to control for exogenous factors beyond weather differences when comparing between baseline and intervention (Demand Side Analytics 2022). Another type of non-routin event is filter clogging in air handling units due to particle accumulation. This can cause supply fans to gradually consume more energy to maintain required duct static pressure Zhai and Nathaniel Johnson (2017). If M&V analysts are unaware of such changes and lack an appropriate adjustment method (e.g., replacing filters before the intervention begins), the savings could be underestimated as increased energy use is incorrectly attributed to the intervention rather than the mechanical issue.

### 1.2.3 Randomized experimental design in other scientific fields

To address the research gap identified in existing M&V studies, particularly the challenges posed by non-routine events, we applied a randomized experimental design method—an approach commonly used in other scientific disciplines. In clinical trials, for instance, randomization is employed to determine the effect of a medical treatment (such as a new drug) by randomly assigning participants to either a control group (e.g., receiving a placebo) or a treatment group Wiley et al. (2016). The primary purpose of randomization is to block confounding variables such as age, gender, and socioeconomic status when evaluating treatment effects. In the context of buildings, a “treatment” refers to a control retrofit, while the “placebo” represents the existing baseline control. Unlike clinical trials, where participants are randomly assigned, our approach randomizes treatment assignment longitudinally for each individual building—an approach known as n-of-1 trials (Gabler et al. 2011). Although the BDG2 dataset allows for randomization at a population level (e.g., across climate zones), building owners are generally more interested in understanding the effects of control retrofits specific to their own buildings, rather than at a generalized population level.

## 1.3 Objectives

As mentioned, the goal of an M&V project is to determine the effect—typically energy savings—of an energy-efficient intervention. In this study, we focus primarily on switchable interventions, which often involve control retrofits. An example of such an intervention is a control retrofit developed by a software-as-a-service company that adjusts the chilled water plant’s supply water temperature based on outdoor weather conditions Qiu et al. (2022). Therefore, we defined the M&V scenario as follows:

*“A company aims to sell its supply temperature reset control software package to a customer, such as a building owner, with a guarantee that it will reduce the building’s electricity usage. If the building owner decides to purchase the service, the company agrees to charge a service fee based on a percentage of the measured energy savings.”*

As required by the M&V scenario, we assessed the performance of both the conventional and the novel randomized M&V methods by estimating the intervention energy savings for all valid buildings in the dataset. By conducting such analysis, we aim to:

1. Compare the energy saving estimation accuracy between the conventional and the randomized method. This study extends the comparison to a large sample of buildings, covering a variety of types and climate zones. The comparison metrics include both estimation accuracy and M&V finishing timeline.
2. Verify the enhanced robustness of the randomized method. By using realistic measurements from real-world buildings, which include various sources of noise, we aim to reflect the challenges faced by building analysts in real projects. As will be demonstrated in the following sections, the randomized approach is less impacted by non-routine events (i.e., measurement ‘noise’), resulting in more reliable energy savings estimates.
3. Demonstrate the implementation of the proposed randomized M&V method using a public available dataset. We ensured the reproducibility of the method by making the analysis code open source including randomized schedule generation, sequential statistical analysis, energy modeling and normalized saving calculation. Using the available open resources, building analysts should be able to seamlessly integrate and apply them in their own M&V projects.

# 2 Method

We outlined the methodology of the study in Figure 2.1 and extended several key components in this section.

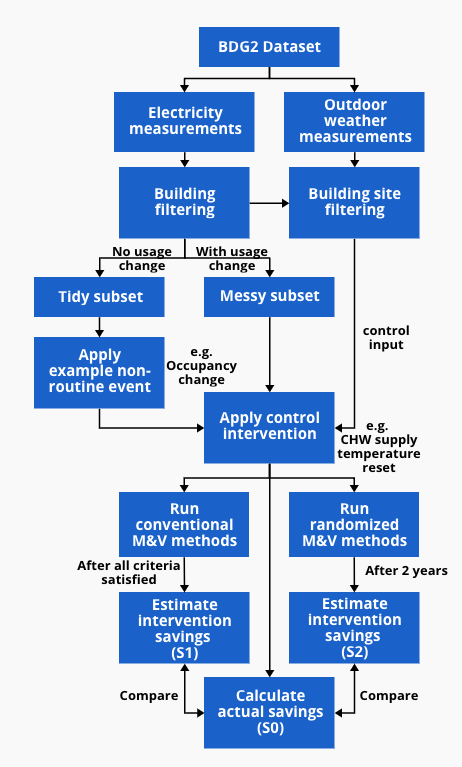


Figure 2.1: Workflow summary of the methodology of this paper

## 2.1 Building filtering

### 2.1.1 ‘Tidy’ subset

In this study, we extracted the electricity measurements from the BDG2 dataset. On a first pass, we filtered out buildings with less noise based on the following criteria:

1. Missing values < 1000: given the hourly resolution of all measurements, this is equivalent to 1.5 months of missing days.
2. Mean electricity usage > 0 kWh: target buildings should have active electricity usage.
3. No statistical significant difference (P-value > 0.05) between the two-year electricity usage: target buildings should have no change in the electricity usage between the two years.
4. Target buildings should have known site location: buildings with anonymous location are excluded due to unavailable typical meteorological weather.
5. Warehouse and parking types are excluded: target buildings have less demand flexibility to implement a chilled water setpoint reset control.

Therefor the resulting subset contains all buildings with ‘tidy’ measurements. Figure 2.2 shows in total, the subset contains 66 buildings in 6 types from 7 different climate zones.

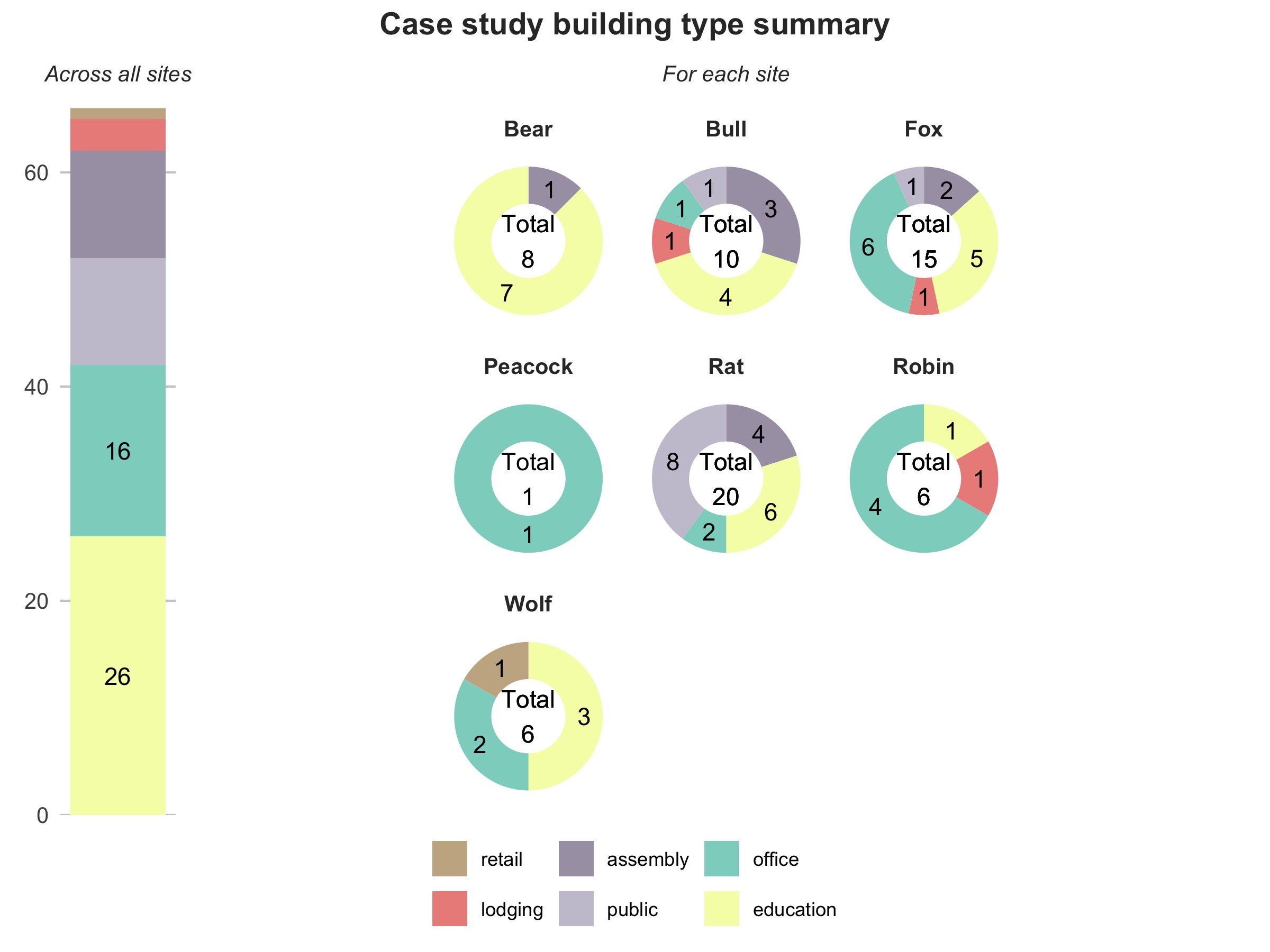


Figure 2.2: Site summary of the tidy building subset

### 2.1.2 ‘Messy’ subset

In reality, the ‘tidy’ subset is less representative of the measurements typically collected from existing building stock, as whole-building electricity measurements collected over two years often show more variability the the filtering critieron. These variations can stem from issues like sensor calibration errors or inherent changes in the building, which, as previously discussed, can bias M&V results. Therefore, to more realistically assess the robustness of the two M&V method, we included an additional ‘messy’ subset which first exclude the ‘tidy’ subset and then re-apply the filtering rule with one amendment:

1. : any increase or decrease of building electricity usage in the second year should be less than 25% of that in th first year.

Figure 2.3 shows the summary of the ‘messy’ dataset, which contains 573 buildings in 12 types from 11 different climate zones.

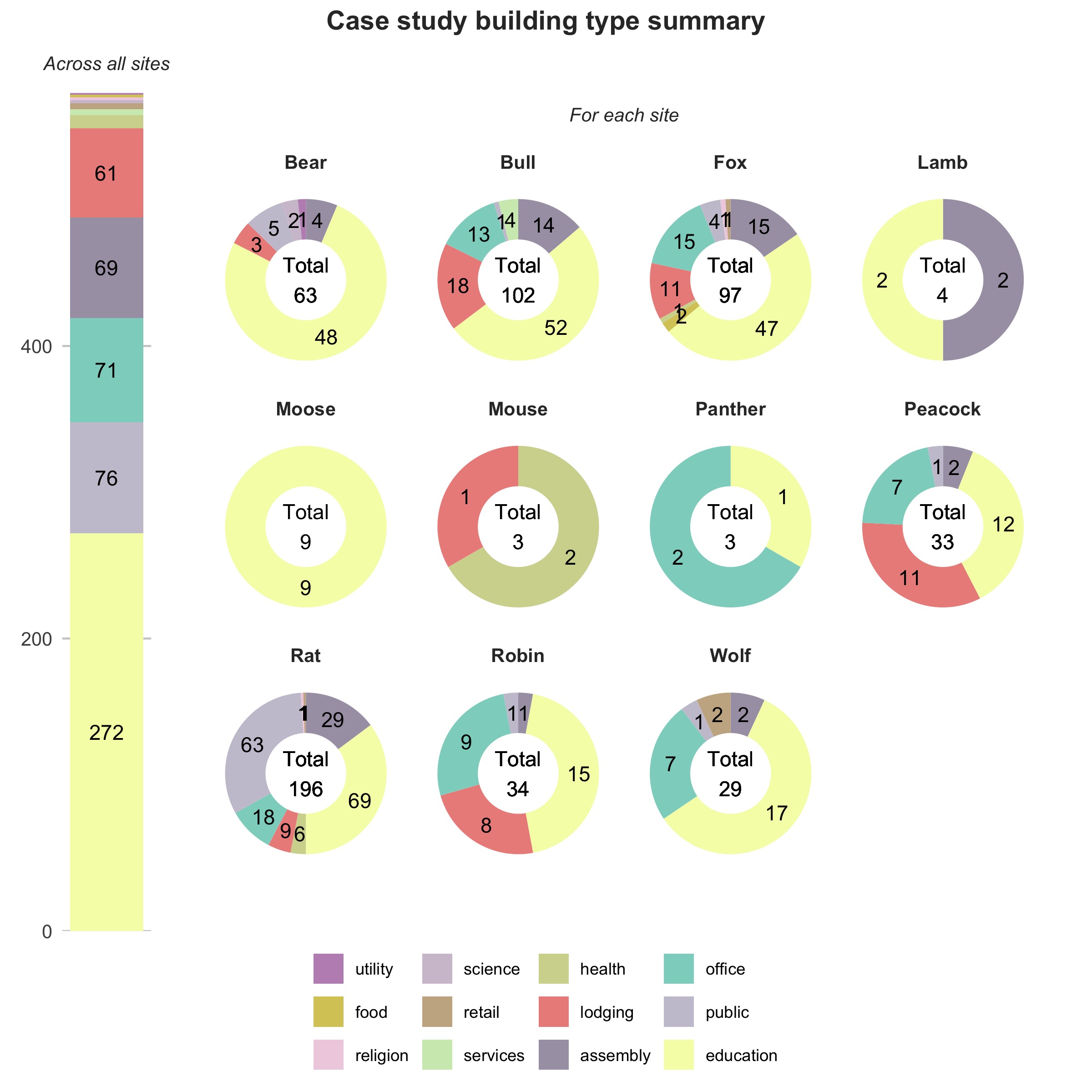


Figure 2.3: Site summary of the messy building subset

## 2.2 Apply control intervention

Figure 2.4 shows the algorithm for the proposed control intervention that reset the chiller supply temperature based on the outdoor weather conditions, which can be commonly found in the literature Čongradac and Kulić (2012). For both strategies, we assume that the chiller is activated when the outdoor temperature exceeds 10°C. The baseline strategy, representing the existing measurements from the dataset, operates with a constant water supply temperature. The intervention strategy, as illustrated in the figure, adjusts the water supply temperature dynamically, resetting it from 7°C to 12°C.

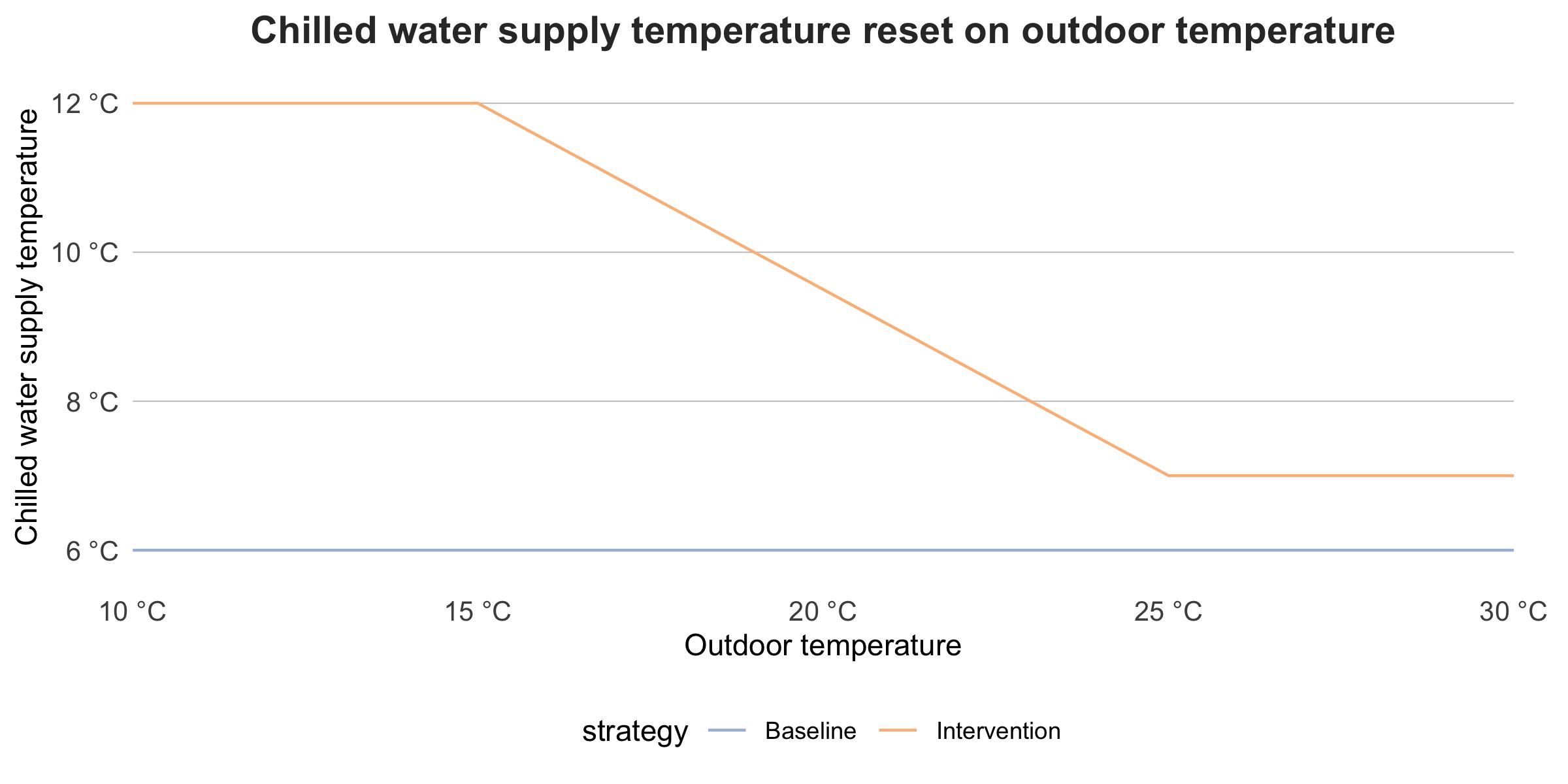


Figure 2.4: Proposed chilled water supply temperature reset based on outdoor temperature

We mapped the chilled water supply temperature reset to the electrical energy savings as:

We assume on average, HVAC systems account for approximately 50% of a building’s total electricity consumption, and the chilled water plant further consumes around 50% of the HVAC electricity. While this assumption largely simplifies the diverse energy usage across various building types, for the scope of this paper, we assume that 25% of the total building electricity is used by the chilled water plant, (Administration 2012). Typically, the savings from an intervention are not proportional to the building’s hourly electricity usage, which is generally the challenge for M&V. To address this, we mapped the resulting electricity savings as a percentage of the plant’s normal operation, calculated as its mean electricity usage over the two-year period. This percentage is influenced by factors such as outdoor temperature (), intervention supply water temperature (), baseline supply water temperature () and hour of the day (, binary indicator whether during peak hours from 9 AM to 4 PM).

Parameters and their pre-defined values are summarized in the table below. For simplicity, those parameters were not rigorously calibrated for each building, and were used uniformly across the dataset.

Table 1. Parameters for calculating the intervention savings.

|  |  |  |
| --- | --- | --- |
| Parameter | Description | Value |
|  | % savings from setting 1 °C higher than | 0.08 |
|  | % savings adjustment during occupied hours | 1.2 |
|  | % savings adjustment during unoccupied hours | 0.8 |

## 2.3 Apply example non-routine event

To illustrate the impact of non-routine events that are not properly adjusted for, we developed three scenarios to quantify the energy consumption changes associated with a hypothetical increase in occupancy. Specifically, we assume that a rise in occupancy in 2016 (referred to as the “baseline year” when using the conventional method) led to a 20% increase in whole-building measured electricity usage. The three scenarios describe when this increase occurred: January to April (S1), May to August (S2), and September to December (S3). This hypothetical change was applied only to buildings in the “tidy” subset, as these buildings were initially more likely to be free from non-routine events.

## 2.4 Run M&V methods

### 2.4.1 Conventional M&V

As described in Section 1, conventional method for M&V is time-consuming and unable to separate non-routine event impact from measured savings. If using conventional method to estimate intervention energy savings, the result (after 24 months) is calculated by the difference between measured intervention and projected baseline in the post-retrofit period. In this study, we leveraged a piece-wise linear regression considering time-of-week and outdoor temperature (TOWT) as independent variables for projection for the counter-factual baseline in the post-retrofit period and normalization on typical meteorological year (Mathieu et al. 2011).

### 2.4.2 Randomized M&V

Compared to the conventional method, the randomized M&V approach offers a more rapid and reliable estimation of energy savings. To apply this method, analysts first define the target savings and stopping criteria. Then they design a randomized switchback schedule and perform sequential statistical tests, such as the sequential probability ratio test (SPRT), to monitor savings as data is collected. Once the target savings are detected, the analysts fit a prediction model (e.g. TOWT) to adjust for differences in outdoor temperature, following the same adjustment process as the conventional method. We provide example switchback experimental design and stopping criteria thresholds below:

* The HVAC system operates from 06:00 to 22:00 each day, so we use a daily sampling interval with the sampling time at midnight each day.
* Block by day of the week with a block period of 12 weeks.

Stopping criteria are:

* A minimum and maximum of 12 and 108 weeks respectively. The randomized schedule covers the entire two-year period but stopping criteria enables an early stop at the end of satisfied blocking period.
* At least 80% of the drybulb temperature range in the annual TMY data sampled by both strategies.
* Test for no carryover effect using a t-test with a p-value not exceeding a defined significance threshold of 0.05.
* 90% confidence that energy savings exceed or do not exceed 0% using the SPRT test. Medium effect size (d = 0.5) quantified by cohen’s d and calculated SPRT statistics either falls below the lower threshold or exceeds the upper threshold.
* As no baseline data is available, test with an equal sampling ratio (50% baseline, 50% intervention).

To remain consistency, savings normalization on typical meteorological year is also modeled through TOWT.

# 3 Results

## 3.1 M&V methods comparison

In this section, we compare the performance of two M&V methods. The key aspects of the assessment include: 1) time required to reach a saving estimation: in most cases, a shorter M&V timeline reduces associated cost and interruption for the building owner; and 2) saving estimation accuracy: this is particularly important for any software-as-a-service company to set a reasonable price with their customers.

### 3.1.1 Savings estimation time

ASHRAE Guideline 14 offering minimum requirements for whole-building measurement path states that the baseline period is either a full range of all independent variables (typically outdoor weather conditions) under normal facility operation or a 12-month worth of continuous measurements. The same requirements also applies to intervention installed in the post-retrofit period. Thus, the conventional M&V method is likely to run over 24 months or even longer due to missing data. For example if an analyst is asked to determine the energy savings of a chilled water plant retrofit but missed most of the cooling season due to delay in retrofit deployment, he/she needs to wait until the next cooling season to measure the savings. If the randomized M&V method is applicable, delays in retrofit deployment pose less risk to the building owner since baseline are continuously monitored. Sampling at equal probabilities (e.g., 50%/50% between baseline and intervention) helps to balance the distribution of independent variables like outdoor weather conditions across all sampled control strategies. As long as one strategy is not sampled over a large number of consecutive days (e.g., 7 days or more), it is unlikely that the measurements of independent variables will differ significantly between the control strategies.

Figure 3.1 shows the average estimated timeline for each building across all sites and climate conditions if using randomized M&V for the applied chilled water supply temperature reset intervention. The timeline figures for each individual building are attached in the supplementary material. The figure shows for all climate zones, covering a sufficient range of outdoor weather condition is the most stringent requirement. However, most buildings can achieve 80% of the required range within 6 months, and all buildings can determine the savings, including associated uncertainties, within 9 months—significantly shorter than the baseline measurement period required by the conventional method.

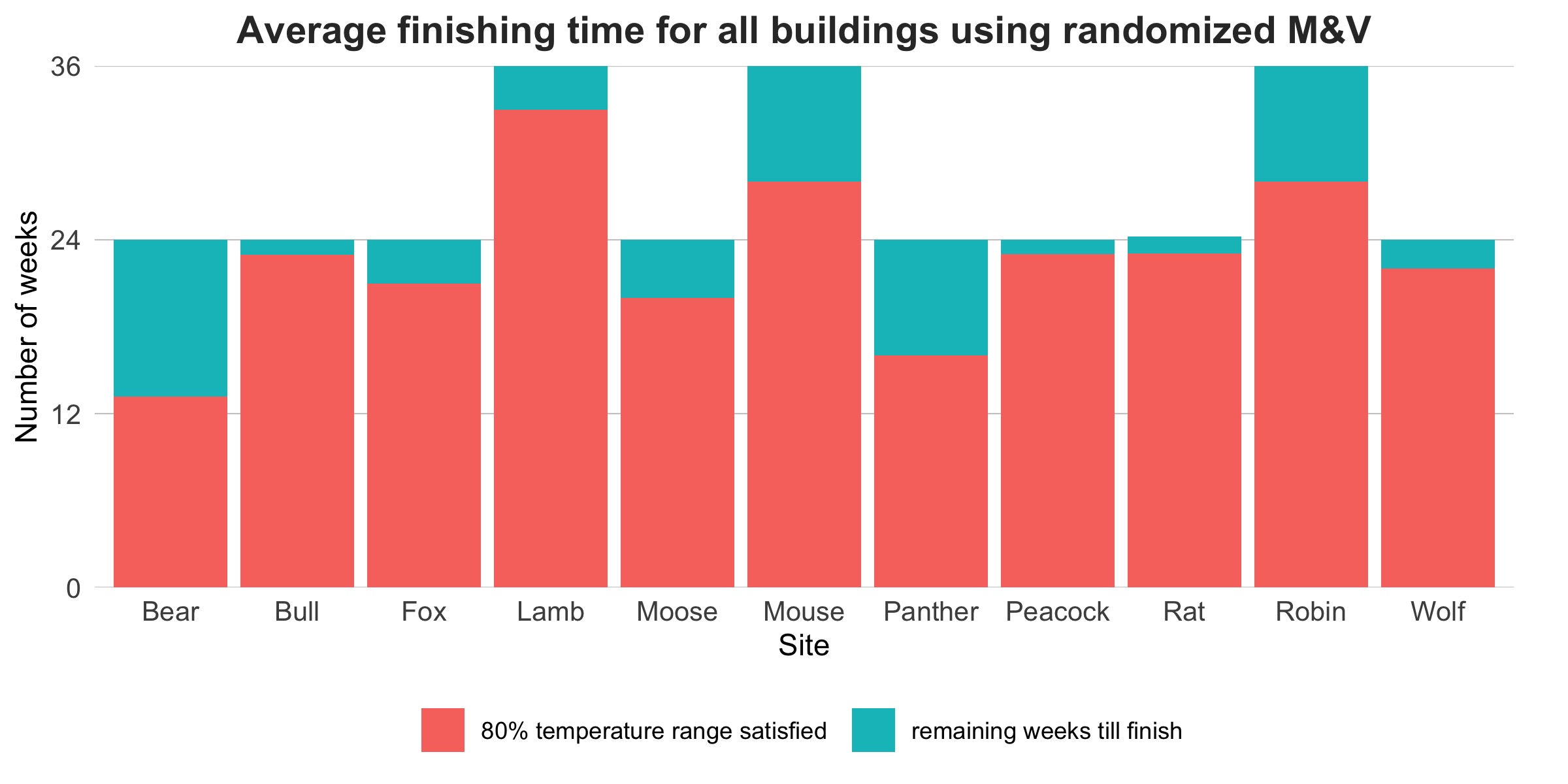


Figure 3.1: Average randomized M&V timeline summary for all buildings at each site

### 3.1.2 Savings estimation accuracy

In this study, we define the overall target savings (i.e., the ground truth) that an M&V analyst aims to detect as the mean reduction in electricity consumption over a two-year period resulting from the implementation of the chilled water supply temperature reset control. This target can be expressed in terms of normalized savings, fractional savings, or simply the measured difference between baseline and intervention measurements. Due to different timeline required by the two methods, we compare the conventional M&V savings at the end of the two-year period with the randomized M&V savings after all criteria are satisfied. Since those are the time in reality, an M&V analyst report estimated savings.

Figure 3.2 shows the overall comparison of the savings estimated for all buildings in both subsets normalized on the typical meteorological year weather conditions of each site. In subplot a), the narrower range and clustering of the true savings indicates the dependence of the intervention effect on the outdoor weather condition, which is intended after weather normalization. Sites with mild climate all year round such as locations in California shows higher savings potential above 10%, while locations with more extreme climate such as Washington DC shows only 6% savings annually. In subplot b), the results indicate that the conventional M&V method tends to estimate savings with greater uncertainty, and its distribution median deviates from the true savings. In comparison, the randomized method, which requires much less time, shows more accurate and precise estimation results.

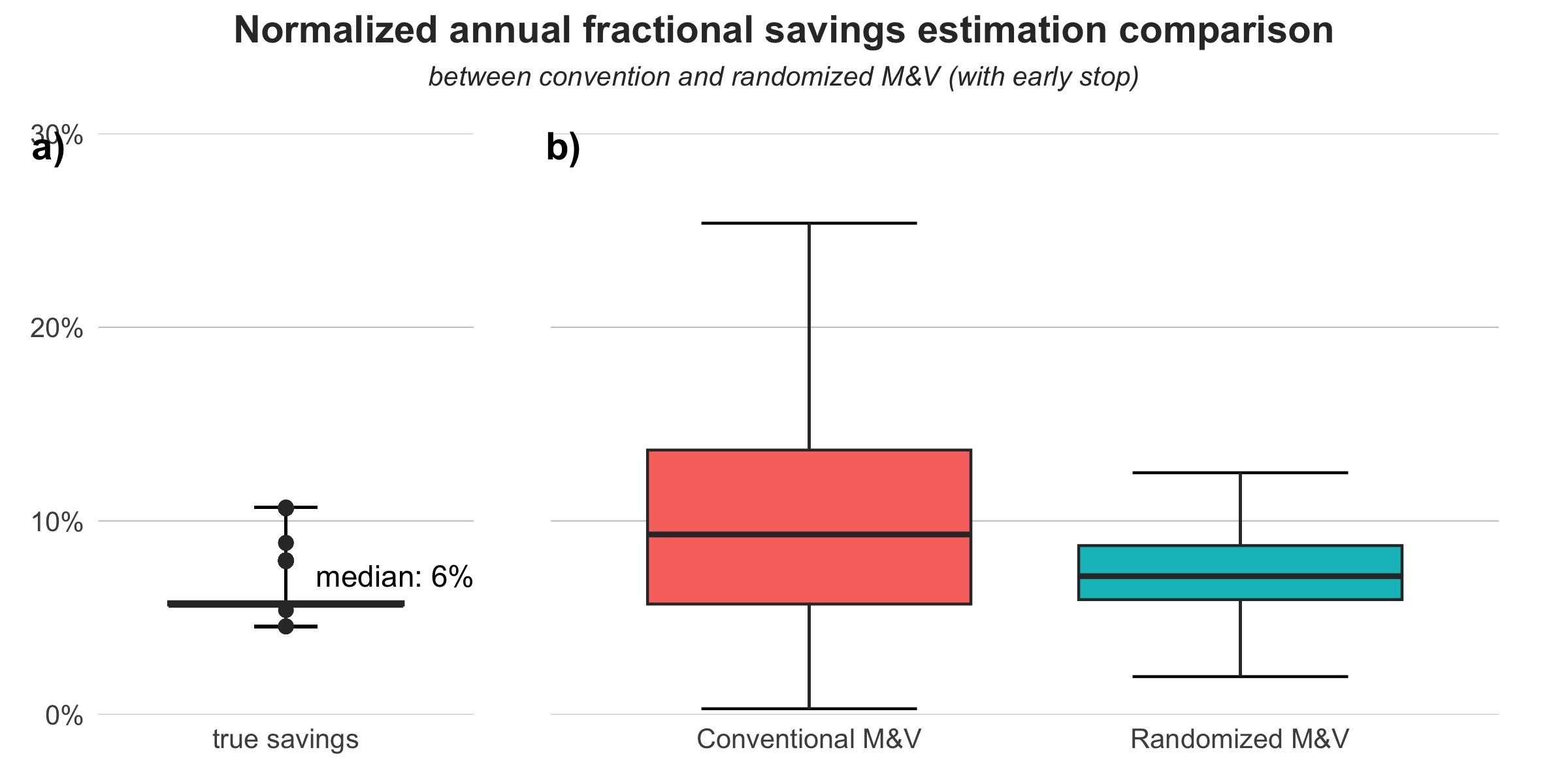


Figure 3.2: Comparison of normalized annual fractional savings on site TMY between conventional and randomized method

To assess accuracy at the individual building level, we calculated the mean absolute difference between the true savings and the estimated savings and normalized the results as a fraction of measured baseline for generalized comparison. Figure 3.3 shows the comparison between the two methods using the tidy subset. In this comparison, we focused on the median and the 95th percentile of the plotted distribution to minimize the influence of outliers. The results indicate that the conventional method outperforms the randomized method in this subset. This is mostly because the tidy subset includes buildings with consistent usage patterns throughout the two-year period, meaning the data used for regression model fitting closely aligns with the conditions during the model prediction phase. In our case, this justifies the TOWT model selection when there is no additional adjustment needed for such pre- and post-analysis.

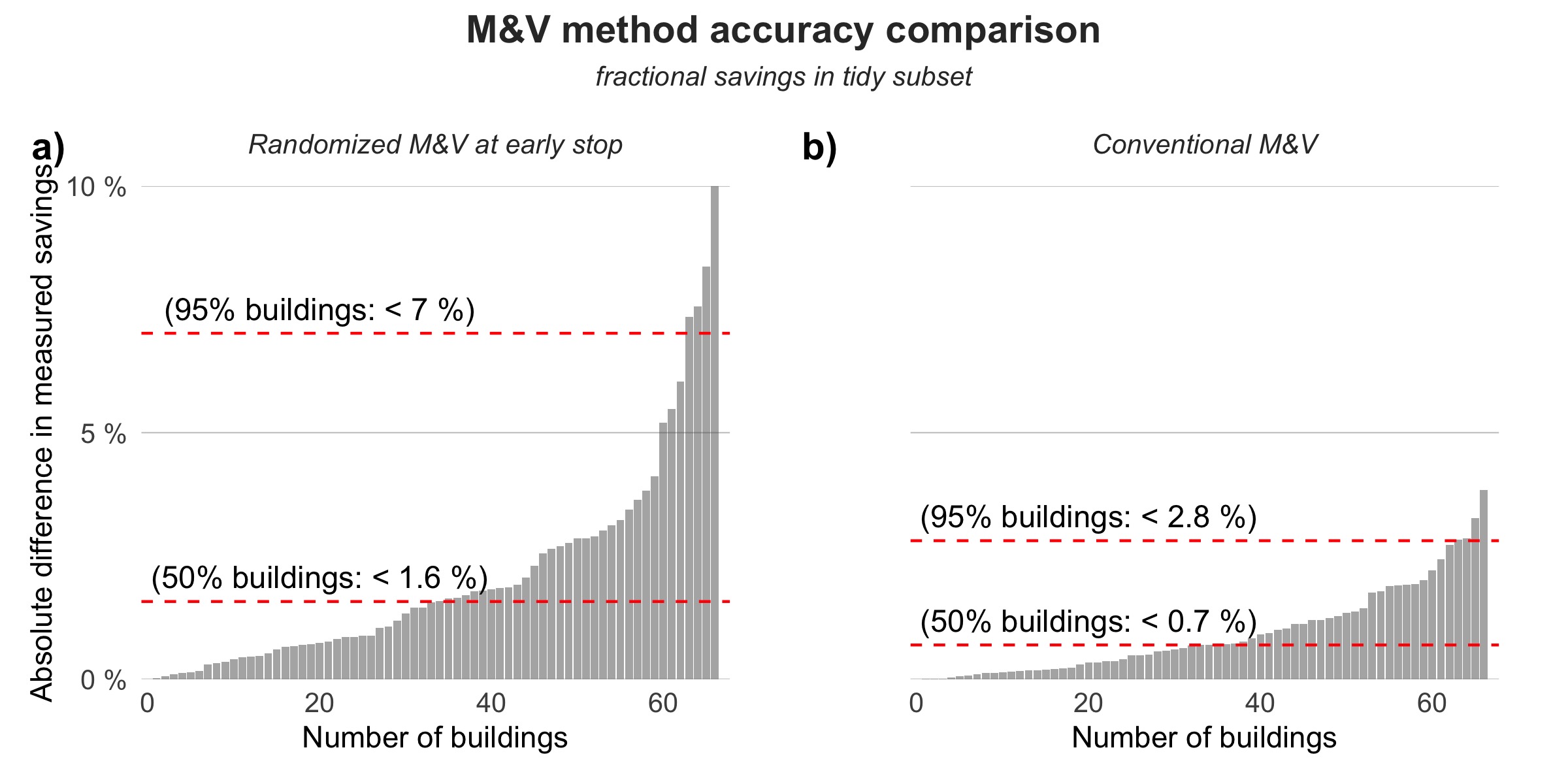


Figure 3.3: Absolute deviation of M&V estimated fractional savings from true target savings using tidy subset

While these findings suggest that the conventional M&V method is advantageous when a building maintains stable electricity usage over time, such stability is rarely guaranteed in real-world scenarios. A more realistic condition is shown in the messy subset in Figure 3.4. In this case, the randomized method demonstrates consistent accuracy in savings estimation, even in the presence of random measurement noise, implying strong robustness. In contrast, the conventional method shows deviations exceeding 5% in approximately 50% of all cases. Non-normalized mean absolute difference comparison plots are provided in the supplementary material. The much deteriorated performance of the conventional method highlights its vulnerability when changes in electricity usage occur. This is because baseline projections based on regression models become unreliable when non-routine events are present. Non-routine events encompass all influential factors not accounted for in the regression model, either due to their impracticality to measure—such as hourly occupancy rates—or their unpredictability—such as a sudden change in building use where an office being converted into a warehouse. We dedicate the following section to continue the discussion of the impact.

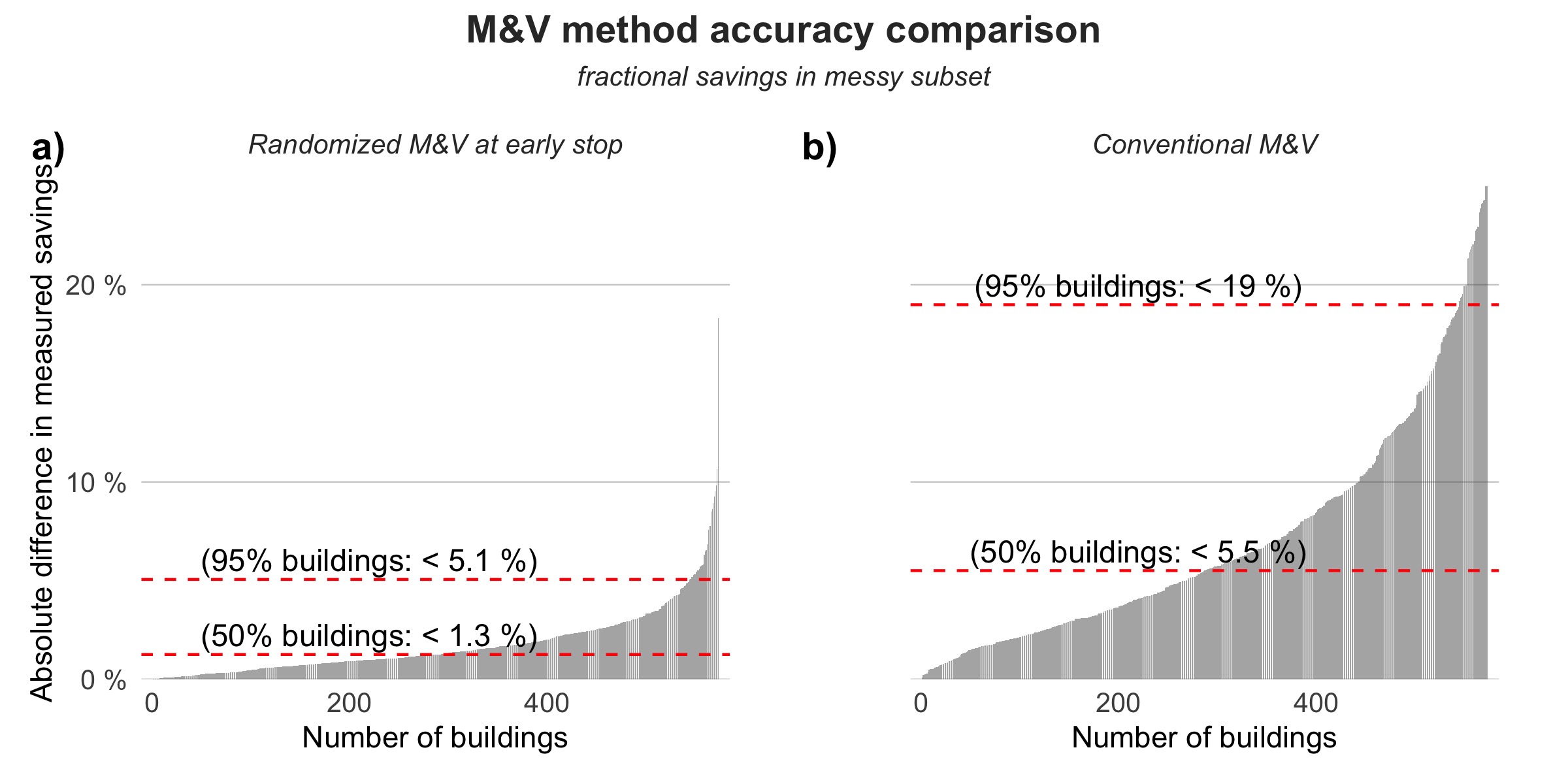


Figure 3.4: Absolute deviation of M&V estimated fractional savings from true target savings using messy subset

## 3.2 Non-routine events impact on savings estimation

In this section, we demonstrate the influence of non-routine events through two scenarios. In the first scenario, we quantified how much occupancy would influence the electricity usage and added to the tidy measurement set as they originally indicates no such change. In the second scenario, we simply run the two M&V methods on the messy measurement sets before adding the chilled water supply temperature reset. Since no intervention is added, the more reliable method should detect a ‘saving’ closer to 0.

### 3.2.1 Occupancy change

Although occupancy can be approximated in several ways in commercial buildings, such as through counting check-in, or WIFI connections, or monitoring indoor CO2 concentration as a proxy. However, it is not a cost-efficient measures to add to the routine operation for most of the buildings and there might be privacy concerns associated. The scenario proposed hypothesize that during the baseline measurement period of the target building, a floor of tenants moved out leaving the space unoccupied for four months before new tenants moved in and this led to a 20% electricity decrease as a result. The M&V protocol only requires the M&V analyst to fit a TOWT model so he/she only measures outdoor temperature. We showed one example in Figure 3.5 where from May 1st 2016 to August 31st 2016, the target building electricity decreased 20% due to reduced occupancy. Thus subplot (a) shows measured baseline with such change, which are then used for TOWT model fitting. Starting from 2017, the occupancy returns normal and only intervention strategy was measured and the projected baseline is the prediction results from the fitted model. To demonstrate, we also plotted the original measurements before adding the intervention effect as ‘adjusted baseline’. This assumes that we can accurately adjust the baseline in the post-retrofit period on back-to-normal occupancy. Subplot (b) shows that the fitted regression underestimate the true baseline condition leading to underestimated savings.

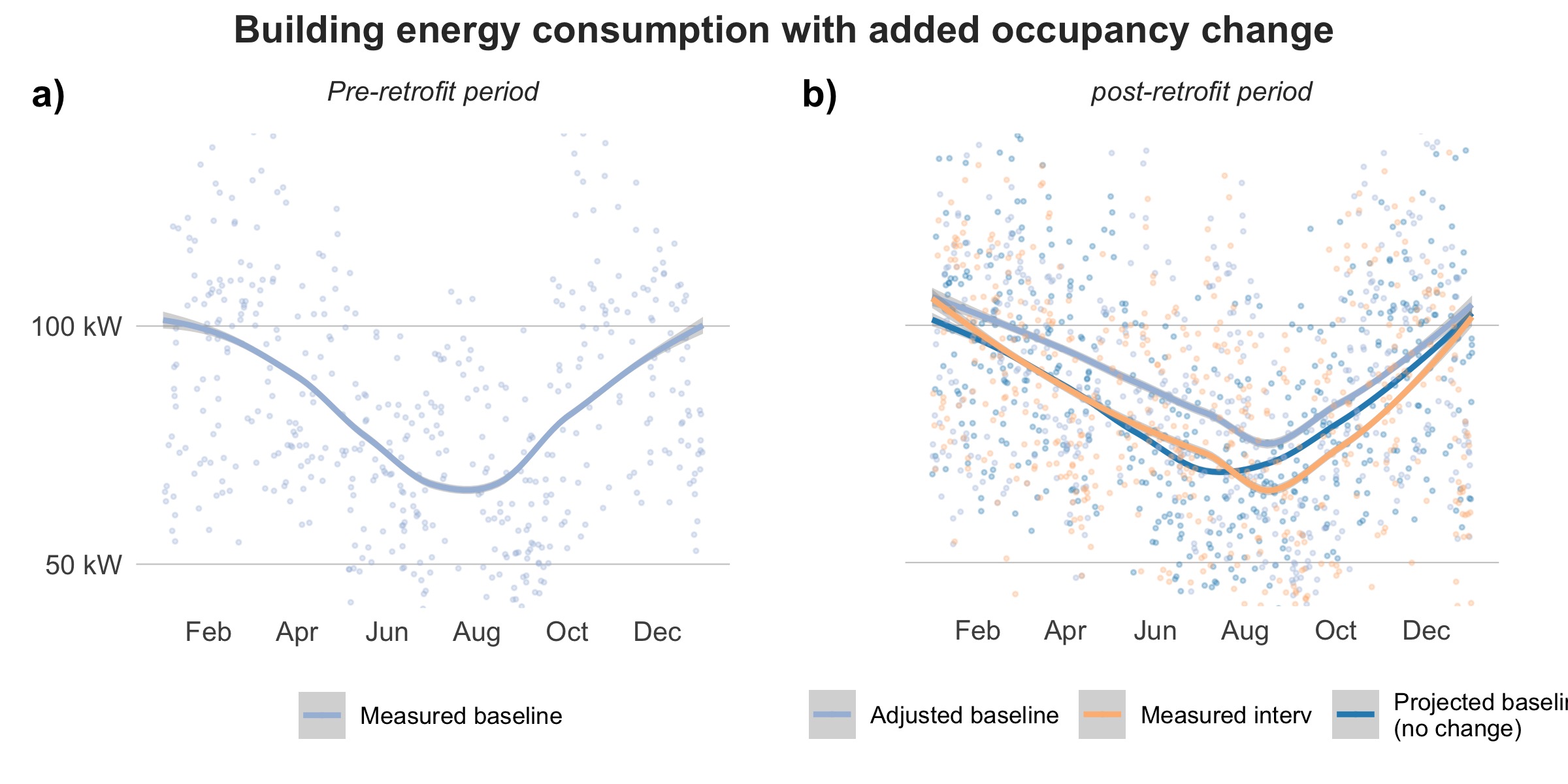


Figure 3.5: Occupancy change impact on TOWT model fitting and baseline projection

Figure 3.6 shows the normalized fractional savings estimation accuracy comparison between the two M&V methods. To compare which method is more robust to the applied occupancy change, a difference-in-difference value is plotted in the figure. Each bar in the plot represent the difference in the deviation of savings estimated by the convention method and the randomized method:

In other words, a positive value indicate the randomized method provides an estimation more aligned to the true target saving. Thus the plot shows the randomized method shows uniformly superior robustness for all sites. The red-dotted line shows the absolute deviation in savings estimation by the randomized method as a reference for scaling. The deviation is consistent with the distribution shown in Figure 2.2 and thus further reinforce its robustness to non-routine events.

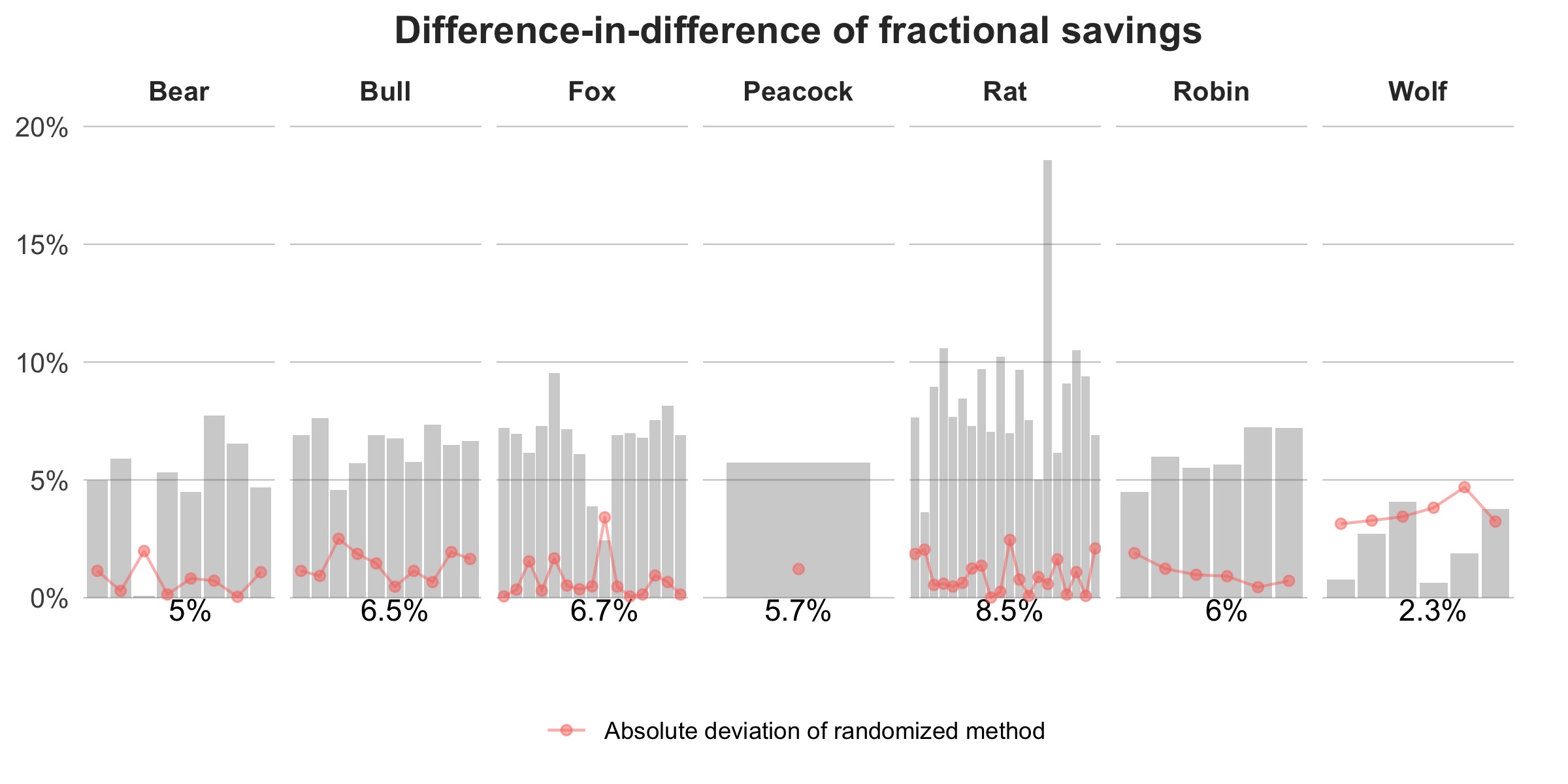


Figure 3.6: Savings estimation accuracy comparison between two M&V methods with added occupancy change (with the site average difference-in-difference displayed at the bottom of each site).

### 3.2.2 No-saving detection

The outbreak of pandemic in 2020 followed by working-from-home policy is a practical example of building energy consumption influenced by non-routine events. During unoccupied months, building energy consumption dropped compared to the same time period in the previous years. If an energy-efficient intervention was deployed onsite starting at 2020, given by the whole-building electricity measurements, the large difference in measured electricity usage in 2020 and projected baseline usage in 2019 can hardly indicate the retrofit intervention effect.

In other words, if there is no intervention applied or the intervention effect is known to be null (e.g. constantly being overriden by the baseline), an ideal M&V method should detect no savings. To test this, we kept the randomized schedule as sampled earlier but removed added chilled water plant intervention effect. Therefore, all sampled intervention days are considered additional sampled baseline days. Earlier we mentioned the ‘messy’ dataset contains some change in the two-year electricity measurement, which is purely due to various non-routine events such as occupancy change or even other measures implemented by the building manager but irrelevant to the chilled water set point reset intervention. Thus, when the proposed chilled water reset intervention was removed, a more reliable M&V method should overcome the influence of those confounding factors and inform no savings.

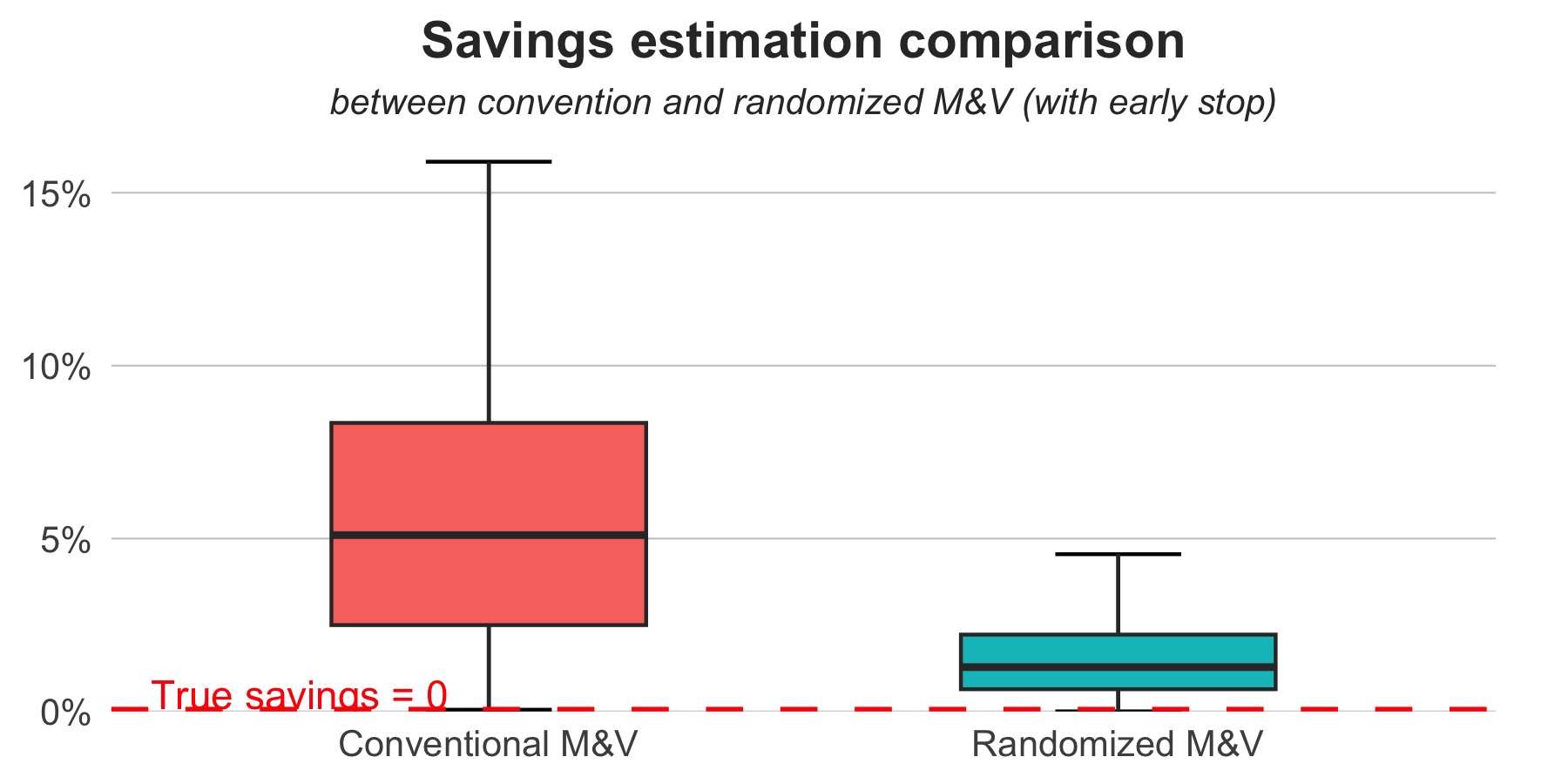


Figure 3.7: Distribution of savings estimation results by the convention M&V method and randomized method.

Figure 3.7 shows that the conventional M&V method in average detected 5% savings when there should be none. The randomized method on the other hand is able to provide an estimation much closer to 0% with reduced uncertainty. This is mostly because when there is a change or disturbance applied to the target building such as lighting retrofit or thermal leakage in the envelope, randomly sample the two strategies at 50%/50% ensures the resulting effect either as a decrease in lighting electricity or an increase in reheat electricity is balanced between the two implemented strategies.

# 4 Discussion

## 4.1 TOWT modeling accuracy

Although this paper argues that regression model prediction results can be largely biased by various non-routine events, we further clarify that this is not related to regression model fitting accuracy. Time-of-week temperature model is used here for its simplicity and convenience since the model only requires outdoor temperature measurements and time of week as independent variables. The model assumes a linear composition of building energy consumption as temperature-dependent and time-dependent load. The time-dependent component accounts for day-to-day variations and the temperature dependent component considers a piecewise linear relationship across a range of temperature intervals.

To assess modeling accuracy, we used the Coefficient of Variation of Root-Mean Squared Error, or CV(RMSE) as the error metric. Since this metric is calculated as a normalized value, it is useful to compare different model fitting results. Guideline 14 requires that whole-building baseline model fitting accuracy should maintain a CV(RMSE) lower than 30%. In addition One study focusing on the baseline energy data-driven model fitting indicates that TOWT performs as accurate as other more advanced machine learning models and the calculated CV(RMSE) distribution for a large sample of commercial buildings indicates a median of 20%. Figure 4.1 plots the distribution of the model fitting accuracy calculated separately for the two measurement sets. The result shows that the TOWT model performance is even better in this study compared to the literature and no significant difference between the two subsets. This is mostly related to low-quality measurement sets filtering in the pre-processing mentioned in Section 2.

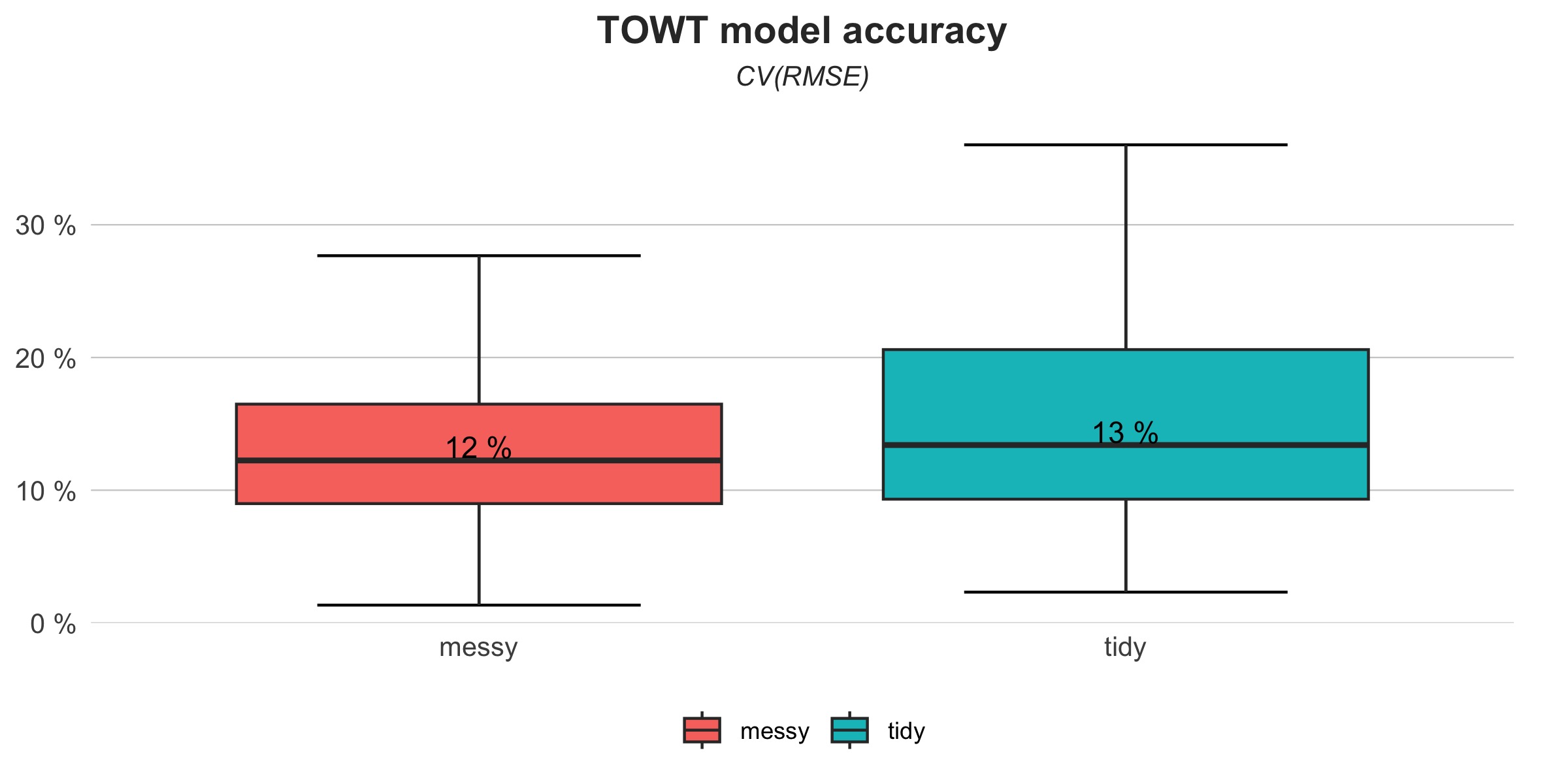


Figure 4.1: TOWT model fitting accuracy distribution on filtered measurement set

In general, the limitation is that despite the regression model tends to capture well on the mean building energy consumption but can underestimate and peak or overestimate the lower base load , which is not useful for assessing demand response. Additionally, a data-driven model can learn the training dataset very efficiently with high accuracy, but the well-trained model is challenging to generalize prediction outside the range of training set.

## 4.2 Sampling ratio for randomized M&V

Another advantage of using randomized M&V is the flexibility of changing sampling ratio after the M&V. For example, the building owner can continue sampling at 50%/50% between the baseline and the intervention to further reduce the uncertainty range associated with the savings. Or he/she can switch to 100% intervention to optimize energy savings, but whether the existing baseline becomes outdated is unknown. A compromised approach is to continue sampling at 80%/20% between the baseline and the intervention. Figure 4.2 shows after the analyst reports the randomized M&V results, a new schedule sampling at 80%/20% was implemented till the end of 2016 and the plot shows the saving estimation accuracy calculated as difference-in-difference when sampled baseline reduced.

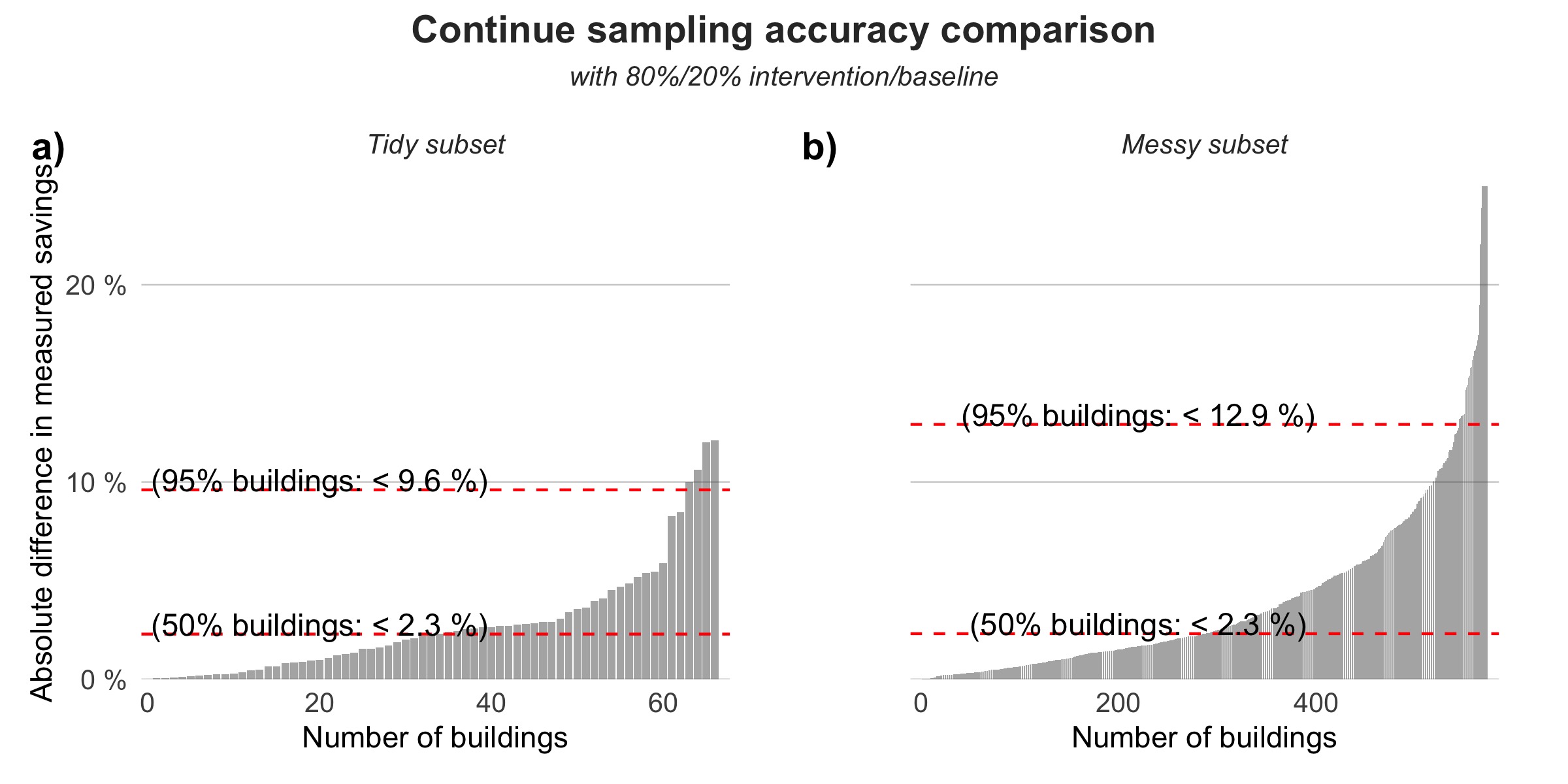


Figure 4.2: Savings estimation accuracy for continue sampling at 80%/20% for 36 weeks after all stopping criteria are satisfied

The deviation remains consistent in the tidy subset but increases slightly in the messy subset, suggesting that changes in energy usage in the target building create a trade-off between measured savings and estimation accuracy when down-sampling the baseline. In this scenario, opting for an early stop at 24 or 36 weeks with 50% intervention and re-sampling 80% till the year end (~ another 20 weeks) still allows the building owner to capture 65% of the full-range savings. On the other hand, if the building owner follows the conventional method, there is no savings due to required baseline measurement.

## 4.3 Limitations and future study

We identify two key limitations of this study: 1) the application of control intervention, and 2) the design of the randomized switchback experiment. While the primary focus is on accurately detecting intervention effects rather than validating their impact, the simulated intervention remains somewhat generic due to the diverse building types and climate zones in the BDG2 dataset. For simplicity, we applied the parameters listed in Table 1 uniformly across all buildings. However, the electricity savings from raising the water temperature by 1°C may be less than 8% in some cases, due to increased chilled water pump speeds. Similarly, the randomized schedule design is also simplified. We assumed a daily sampling interval would be sufficient for most commercial buildings, but exceptions exist, particularly for buildings with significant thermal lag in heating and cooling systems, such as those with heavy concrete construction, hot water tanks, or Thermally Active Building Systems (TABS). In such cases, the effect of a previously sampled strategy can carry over and influence subsequent measurements due to thermal storage, known as the carryover effect. For example, if the intervention pre-charges chilled water in thermal mass one day before switching back to the baseline, the analyst is likely to observe reduced energy usage in the following days. This study does not account for the carryover effect, but in practice, we recommend using a 3-day sampling interval and dropping non-consecutive days to ‘wash out’ any lingering effects from previous strategies.

Our major goal for the future study is to further extend the application of the proposed randomized M&V. For example, a customer maybe interested in whether a Model Predictive Control (MPC) can reduce energy bill under dynamic pricing structure and what the estimated Return of Investment (ROI) for the retrofit is. Or whether a load shift control can save operational cost by shifting load from grid peak to off peak period. Furthermore, the novel method is generalizable beyond energy saving M&V cases. The statistical analytic framework is applicable to a variety of retrofit metrics such as indoor air quality, operational carbon emissions and thermal comfort.

# 5 Conclusion

This research demonstrated the usage and assessed the performance of a novel whole-building measurement and verification method using a large open-source commericial dataset. The method leverages the randomized experimental design concept from other scientific research fields and statistical sequential inference techniques to inform whether a target savings are detected. We made an example of chilled water setpoint reset based on outdoor weather condition as a virtual control retrofit use case and applied to over 500 filtered commercial buildings. By comparing the savings estimation by the conventional method (outlined in ASHRAE Guideline 14) and the novel randomized method, we showed that the randomized method is able to provide a more rapid and robust saving estimation.

We showed that throughout 7 climate zones we assessed, the randomized M&V can provide a saving estimation by 36 weeks (with the majority finishes by 24 weeks) once all stopping criteria satisfied. Meanwhile, the conventional method requires a full range measurement of both baseline and intervention performance under normal operation conditions, which normally translate to 6 - 9 months each. We further showed the estimated savings at early stop has acceptable accuracy when compared with the true calculated savings.

We also assessed the impact of non-routine events on the proposed M&V method both by 1) adding a known change, such as occupancy-induced energy reduction, and 2) detecting removed intervention when no reset is applied to buildings with a marginal difference in energy consumption. We showed in both scenarios that baseline model fitting can be biased while the randomization can efficiently block those confounding effect to ensure the robustness of the saving estimation.

Although the limitation of the method is that it only applies to a subset of all M&V use cases (i.e. only if the strategy can be switched on and off), we believe the true value lies in the usefulness for most control retrofit validation in the field test.

# 6 Acknowledgements

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