NATIONAL RENEWABLE ENERGY LABORATORY

Metering Best Practices Applied in the National Renewable Energy Laboratory's Research Support Facility

A Primer to the 2011 Measured and Modeled Energy Consumption Datasets

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Nomenclature

DOE	U.S. Department of Energy
ERE	energy reuse effectiveness
EUI	energy use intensity
FEMP	Federal Energy Management Program
HVAC	heating, ventilation, and air conditioning
M&V	measurement and verification
NILM	non intrusive load monitoring
NREL	National Renewable Energy Laboratory
NZE	net zero energy
PUE	power utilization effectiveness
PV	photovoltaic
RSF	Research Support Facility

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1.0 Introduction

Modern buildings are complex energy systems that must be controlled for energy efficiency. The Research Support Facility (RSF) at the National Renewable Energy Laboratory (NREL) has hundreds of controllers -- computers that communicate with the building's various control systems -- to control the building based on tens of thousands of variables and sensor points. These control strategies were designed for the RSF's systems to efficiently support research activities. Many events that affect energy use cannot be reliably predicted, but certain decisions (such as control strategies) must be made ahead of time. NREL researchers modeled the RSF systems to predict how they might perform. They then monitor these systems to understand how they are actually performing and reacting to the dynamic conditions of weather, occupancy, and maintenance.

This report describes how the B and C wings (a total of 220,000 ft^2) of the RSF were equipped for monitoring its energy use, how its systems were modeled to forecast their energy use, and how those systems actually performed in 2011. An accompanying dataset presents the hourly energy use of the RSF's systems aggregated by end use into the following categories: cooling, heating, mechanical, lighting, plug loads, data center, and photovoltaic (PV) generation. The forecasted values for these systems are included along with the actual performance. Finally, a dataset matching pertinent weather information to each hourly data point is included for reference. For more information on the RSF, visit the Research Support Facility Web site.

2.0 Designing an Energy Metering System for a Commercial Building

This section discusses metering best practices and highlights the metering approach that NREL has taken in the RSF. A rationale is provided for each aspect of the metering system design. For a comprehensive guide on metering in commercial buildings, please refer to the Federal Energy Management Program's (FEMP) Metering Best Practices guide [1]. Torcellini et al. studied six high performance buildings, and found that metering leads to better management and improved energy performance [2].

2.1 Step 1: Establish Metering Objectives Upfront

Making a metering plan is perhaps the most important aspect of designing a metering system, and at the same time, the most commonly overlooked. Figure 2-1 is a graphical representation of the metering plan that was implemented in the RSF's data center to be able to calculate Power Utilization Effectiveness (PUE) [3]. This graphic helped multiple parties at NREL understand the metering plan and buy in to the energy performance goals of the RSF.

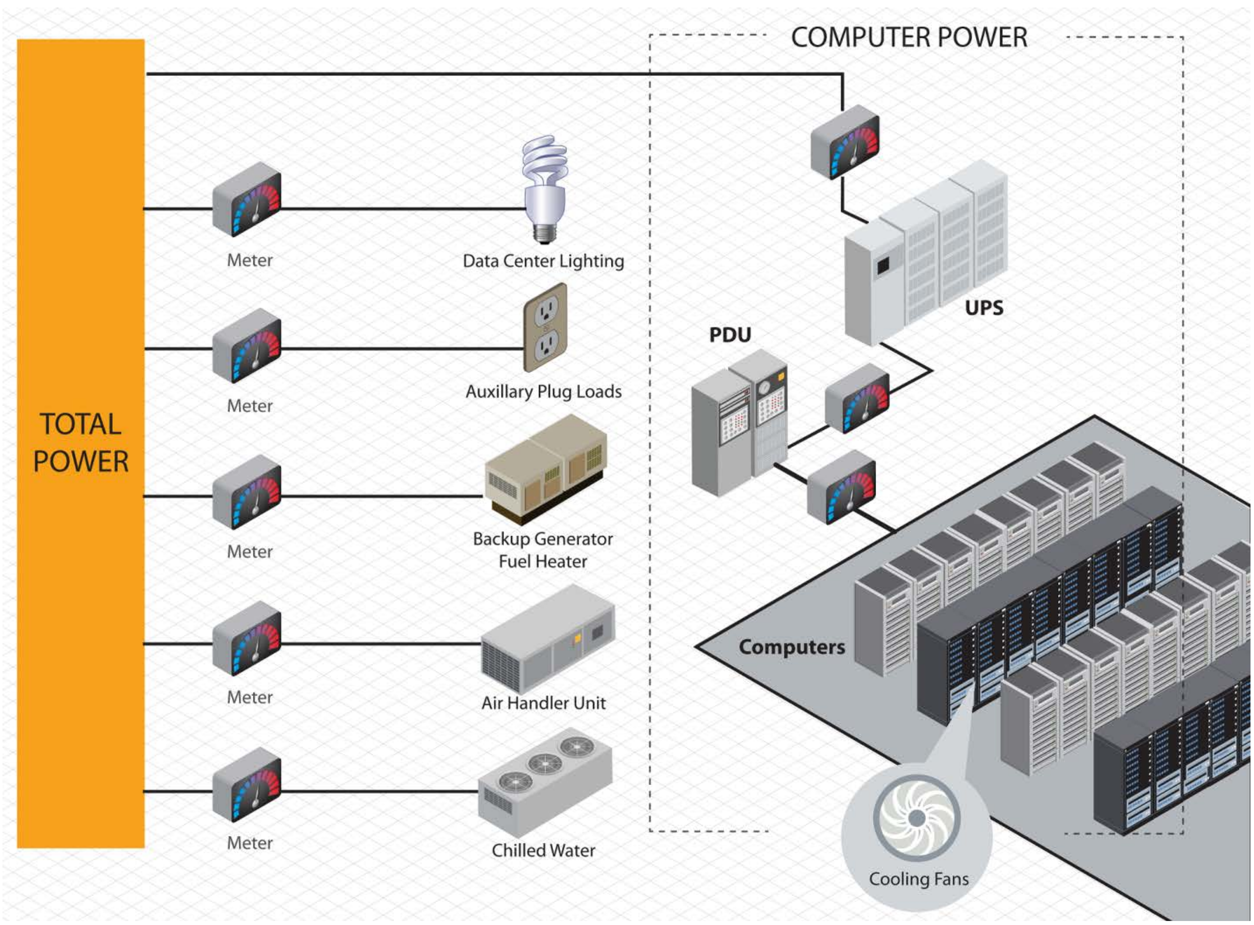

Figure 2-1 Diagram of the power meters in the RSF data that allow PUE calculation (Credit: Marjorie Schott, NREL) [3]

When a metering system is not well planned, it leads to more laborious and computationally-intensive post-processing of collected metered data. It can also result in insufficient metering: a situation where there are not enough metered points to calculate key energy metrics. Insufficient metering makes it difficult or impossible to effectively conduct continuous commissioning, measurement and verification, and energy benchmarking. If some energy end uses (HVAC, lighting, plug loads, heating, cooling, etc.) are incompletely metered, there may be insufficient data to spot improvements or degradations in whole-building and building system performance over time.

The RSF was designed to meet strict energy goals. One goal was to achieve a whole-building demand-side energy use intensity (EUI) requirement of 25 $kBtu/ft^2 \cdot yr$. Another goal of the building was to be net zero energy (NZE). An NZE building consumes as much energy as it produces (via its PV system) annually. Therefore, the first step in designing the metering system for the RSF was to recognize that NREL would want to be able to quantify annual whole-building EUI and NZE status with metered data.

2.2 Step 2: Decide How "Detailed" Your Metering Should Be

The more sensors that are deployed in a building, the more "detailed" a metering system is considered to be. A metering system can be very "macro," using only one whole-building electricity and one whole-building gas utility meter. Conversely, a metering system can be very "micro," having a meter on every electrical circuit and at every piece of gas-consuming equipment. Typically, the number of sensors that are deployed in a building is determined by budget. One pitfall that many metering systems encounter is that they aren't designed to monitor energy end-uses or certain key equipment because they aren't called out in the goals of the project -- given the expense of a detailed system. However, facilities- and energy-managers can use this level of metered data to investigate and track down equipment that isn't working properly.

The metering system in the RSF strikes a balance between macro and micro. There is sufficient metering to be able to fully account for all of the energy end uses, and to individually monitor the performance of some of the building's key equipment (such as the transpired solar collector). Plug load metering is an example of how the RSF strikes a balance between macro and micro. The RSF was not set up to meter each plug load circuit separately (a micro level of metering). Instead, all plug load circuits are organized onto dedicated panels and each panel is metered. This provides a sufficient level of detail to quantify whole-building: plug loads, EUI, and NZE status. Thus, the energy goals of the building are able to be met without over-metering or under-metering.

2.3 Step 3: Select Meters

A vast selection of metering equipment is currently on the market. Metering systems vary widely in their accuracy, price, ease of installation, and advanced/smart features. The energy meters in the RSF have an accuracy of $\pm$ 5% or better. The energy meters in the building are all appropriately sized for the electrical circuit or other variable being monitored. For example, a current transducer (CT) that is rated for 32 Amps would be inappropriate for monitoring a circuit that draws a current of 100 Amps. Likewise, an ultrasonic flow meter that is rated for up to a 6-in. diameter pipe would be inappropriate for monitoring the flow in an 8-in. diameter pipe.

2.4 Step 4: Select an Appropriate Sampling Interval

Sampling interval refers to how often a meter takes a reading. When measuring power and energy consumption (typically kilowatts and kilowatt-hours, respectively), the sampling interval must strike a balance between: (1) being fast enough to capture key peaks and valleys of system operation throughout the day; and (2) not being so fast that data analysis and storage are cumbersome because of the high volume of data being collected. In general, energy meters should be able and configured to take readings at least every 15 minutes.

The electric energy meters in the RSF take readings every 5 minutes. Weather conditions are monitored by an array of sensors that take readings every minute. The collected data are typically downsampled (through averaging) to 1-hour intervals for ease of data analysis.

2.5 Step 5: Install Meters and Verify Meter Output

In existing buildings, the installation of meters should be coordinated so that daily building operations are not disrupted or impeded, if possible. In new construction, the installation of meters should be completed before the building opens. Every measure should be taken to keep the metering system out of sight of the building occupants. Unauthorized access to the metering system and its components should be prohibited to ensure and maintain data integrity and preserve safety.

Once installed, the metering system in the RSF was properly calibrated according to the manufacturer's recommendations and the output of the system was verified and validated to ensure it is measuring and recording accurately. The metering system is maintained and operated according to the manufacturer's recommendations, and will likely require periodic calibrations.

The metering system in the RSF is designed to ensure monitoring quality. In many cases, faults in the metering system can be identified via an energy balance. For example, the sum of the energy end-use meters should equal the sum of the main electricity and gas meters (within the accuracy range of the meters). The RSF metering system facilitates remote monitoring of all the measured points back to a central data logger that enables users to remotely access the data in real time and analyze it for faults.

2.6 Special Considerations for New Construction and Extensive Retrofits

In new construction and extensive retrofits, it is advisable to set up the electrical infrastructure such that the energy end uses are aggregated onto their own dedicated electrical panels; this is typically cost prohibitive in a minor retrofit. For instance, in the RSF, there are electrical panels dedicated to only: plug loads, lighting, mechanical, and the data center. This approach makes metering much simpler because an entire panel can be metered with just one meter and an entire energy end use can be captured. Not taking this approach requires many meters to be used, which may need to be added and/or subtracted to isolate each energy end use. For example, if Panel X has all the building's plug loads on it and one lighting circuit (say on Circuit Y), the plug load energy end use for the building would be $Meter_{Panel\ X} - Meter_{Cicuit\ Y}$. Therefore, organizing electrical circuits onto panels that are dedicated to just one energy end use reduces upfront capital costs for the metering system and the required data post-processing.

2.7 Special Considerations for Existing Buildings

It is a common practice to add more electrical circuits to a building as they are needed over time. Also, circuits may be repurposed for a completely different energy end use during a retrofit. This adds an extra layer of complexity when designing a metering system. When designing a metering system for an existing building, two key items must be verified: (1) meters are being installed on the correct circuits; and (2) all the energy consumption for a given building system or energy end use will be captured by the circuits that are metered. There are several steps to verify these two key items:

1. Locate the electrical 1-line diagram and panel schedules for the building.
2. If possible, meet with the electrician or engineer who created the 1-line diagram to verify whether changes have been made to the electrical infrastructure since the diagram was created.
3. If the electrician or engineer is absolutely certain that no changes have been made, base the metering system design on the 1-line diagram and panel schedules.
4. If changes have been made, use circuit tracing to verify, at a minimum, the new circuits that have been added.
5. Update the 1-line diagram and panel schedules and base the metering system design on these documents.

An alternative approach to circuit tracing is nonintrusive load monitoring (NILM). This technology uses metering at the branch circuit level. NILM relies on a library of equipment electrical "signatures" to identify loads that are being fed through a given branch circuit. One advantage to this technology is that it does not require circuit tracing, and save significant time. One disadvantage is that not every load may be in the NILM library, so some loads will be unidentified. This makes it difficult or impossible to fully account for every energy end use in the building.

3.0 Analyzing Metered Data to Draw Conclusions About Energy Performance

Once the metering system is installed and calibrated, the next steps are to collect and analyze the metered data to assess and draw conclusions about energy performance.

3.1 Step 1: Download the Data

The first step is to download the data. This step may be easy or difficult, depending on the manufacturer of the metering and data logging equipment. Metered data from the RSF are downloaded via a Ruby script in comma separated values (CSV) format. Other file formats will work, but CSV is usable by many programs across multiple platforms.

3.2 Step 2: "Clean" the Data

No matter how carefully a metering system is designed and installed, the metered data will have errors, which may include data stream cut-outs resulting in missing data, extreme meter spikes, missing or overlapping timestamps, and erroneous values (such as lighting circuits reporting negative power values). If a meter is regularly producing erroneous data, it should be re-calibrated or replaced as necessary.

The 2011 RSF dataset that accompanies this report has already been "cleaned" (the errors have been removed). Keep in mind that "clean" data are not the same as "perfect" data. Engineering judgment was used to replace missing or erroneous data. The most commonly used data cleaning techniques that were used on the 2011 RSF dataset follow:

- If 1 hour or less of data was missing, simple, linear interpolation was used to fill in data.
- If more than 1 hour of data was missing, data from a typical hour during that same time-of-day or day-of-week were used to fill in the gap.
- Erroneous values were corrected as logically as possible. For example, if a meter that should only have positive kilowatt values reported negative values, the data for those timestamps were corrected to a value of zero.
- Extreme meter spikes were flagged based on whether they were three standard deviations (or more) above or below the average value for that meter. Simple, linear interpolation was used to fill extreme meter spikes.

3.3 Step 3: Aggregate the Data

Once the data have been cleaned, meters should be aggregated (if desired) resulting in key building performance parameters, such as whole-building energy end uses, energy use by space type, and gross or net building energy use. In the RSF, the meters are aggregated into whole-building energy end uses, which include:

- Cooling
- Heating
- Mechanical
- Lighting
- Plug loads

- Data center
- PV production.

3.4 Draw Conclusions About Energy Performance

Once the data have reached this point, building energy performance metrics for the RSF, such as EUI and NZE status, are calculated. For the RSF data center power utilization effectiveness and energy reuse effectiveness are calculated (see reference [3] for more information).

Key graphs that are generated each month to assess building energy performance are:

- Outdoor air temperature versus heating load
- Outdoor air temperature versus cooling load
- Typical 24-hour weekday load profile for each energy end use
- Typical 24-hour weekend load profile for each energy end use
- Stacked bar chart with a bar for each of the 12 most recent months; all the energy end uses are stacked in each column.

3.4.1 Compare Metered Data to an Energy Model

We can strive for perfect energy efficiency of a building during the design phase; however it is its operation that dictates its performance. Comparing actual performance (metered) with expected performance (modeled) is key to understand corrective actions to ensure performance as originally intended. The modeling approach that was used in the RSF is documented in detail by Hirsh et al. [4]. The results of the RSF energy model for 2011 are included in the dataset that accompanies this report.

A few items need to be checked when comparing measured data to modeled data:

1. The sampling rate of both datasets must match. For example, if the modeled data are in 1-hour intervals, the measured data must be adjusted to 1-hour intervals to facilitate comparisons.
2. The date range of interest needs to be matched between the measured and modeled data. For example, to compare measured performance to the energy model for January 2011, be careful to only compare data from that month in both datasets.
3. The units must match between the measured and modeled datasets. For example, if the modeled data are in gigajoules and the measured data are in kilowatt-hours, then modeled data should be converted into kilowatt-hours.

4.0 Discussion of the Accompanying 2011 RSF Dataset

This report provides an explanation of how the RSF was set up for metering and how metered data are analyzed to track energy performance over time. The accompanying datasets include hourly measured and modeled energy data as well as measured weather data for 2011. The report and datasets can be used by energy modelers, building science students, building energy managers, and others to further their understanding of metering and analyzing the performance of buildings.

There are a few things to note about the 2011 RSF dataset:

- To account for the unquantified efficiency of delivered hot water from NREL's central plant, the 2011 RSF dataset has assumed/accounted for a fixed delivered hot water efficiency of 90%. The hot water efficiency is based in a high efficiency natural gas boiler.
- To account for the unquantified efficiency of delivered chilled water from NREL's central plant, the 2011 RSF dataset has assumed/accounted for a fixed delivered chilled water efficiency based on a COP of 3.0. The chilled water efficiency is based on code minimum air-cooled chillers.
- The central plant energy use is included in the overall demand side EUI requirements.

5.0 References

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Appendix A Link to RSF Datasets

NREL RSF Measured Data 2011
http://en.openei.org/datasets/node/933

NREL RSF Weather Data 2011
http://en.openei.org/datasets/node/934

NREL RSF Energy Model 2011
http://en.openei.org/datasets/node/935