Key Performance Indicators and Analysis for Commercial Buildings with System Level Data

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ABSTRACT

This report describes New Buildings Institute's (NBI) investigation of metered performance indicators (KPIs) for commercial building energy use. These are indicators that can be observed or benchmarked using more detailed system-level meter data beyond whole-building energy data. This is the last stage of work that began with applying whole-building energy analysis approaches for energy use feedback. Subsequent stages used more time and labor intensive onsite audits. This report summarizes the installation of additional system level metering downstream of whole building meters to investigate what KPIs can be observed and benchmarked, what they indicate, and how energy performance reviews can be enhanced while still using only limited additional metering.

This report describes the results from two office buildings outfitted with system level metering to calculate KPIs. Building designers are the primary audience, followed by operators, and occupants though the results for these last two groups are not presented in detail in this paper. Where possible KPIs were benchmarked using data from NBI's building performance database or other data to expand the comparisons.

The findings show that calculated system level KPIs can provide an orderly way to better define superior or inferior performance of certain aspects of design, operations or occupant behaviors. These KPIs can also be used to ensure that buildings compared using whole building methods are similar in their design, operations, or occupants to improve the reliability of conclusions.

Since the definitions of each "system" are crucial to the usefulness of the KPIs, or any other system level metrics, the paper provides those definitions used for the research and highlights the need for coordination among policymakers and practitioners on consistent definitions of metering, application, and performance metrics.

This paper begins with a discussion of the approach, describes the system level definitions, presents the Designer KPI results, and summarizes conclusions from the two sites.

INTRODUCTION

NBI conducted this research under Task 2.4 of the PIER Evidence-based Design and Operations Program to identify key performance indicators (KPI) representing major and consistent variables affecting building energy use. The research intent was to distinguish a set of KPIs that provide intuitive and impactful feedback from a minimum of metering points and develop a feedback format that is understandable and actionable.

In the preceding tasks we examined KPIs for 22 commercial buildings' energy performance using different methods: whole-building energy analysis, in particular NBI's FirstView[TM] tool [Turner and Reichmuth 2011], detailed sensitivity analysis modeling, and site visits and assessments. In each stage we gathered a greater level of detail but reduced the number of buildings from the initial analysis as the depth of analysis increased.

Our conclusions from these earlier stages pointed to certain KPIs based on observations of commercial building attributes and the correlating monthly utility metered data or results of the sensitivity modeling. The current stage of work sought to use a greater level of detail through system-level metering on 2-4 buildings to expand the KPIs beyond whole-building metered or simple observed building attribute metrics.

The report describes the results of the system-level metering in two office buildings; a 14,000 square foot (SF) Oakland Office in Oakland, California and a 5,500 SF Vancouver Office in Vancouver, Washington. We used gross floor area for the SF measurement. The selection criteria was based on finding a suitable tenant with high performance systems in place and a clean design of the distribution of electric and fuel to minimize the metering points at the system level to stay within the project budget. Although the design community considers it "good practice" to isolate loads by system type (i.e. lighting, plug loads, HVAC), it remains common to have an intermingling of loads on shared electric services, resulting in many of the initial buildings requiring too many meters to realistically capture the defined system.

In a commercial building, the "system" refers to an aggregate total of all the usage, electrical or fuel, by a particular class of equipment. Frequently used categories are plug loads, lighting, and HVAC, with additional categories depending on the definer. We addressed this issue of defining system loads in System Level Metering, Capabilities, and Definitions below. We collected system loads by installing sub-meters (advanced interval meters downstream of the main utility meter) at key points in the building where the system loads were aggregated.

The system-level KPIs in this stage of the project serve to inform the designers, operators and occupants and were looked at in two ways:

(1)   How do these KPIs directly inform designers, operators and occupants?
(2)   How do these KPIs help classify buildings for more accurate whole-building analysis?

As an example of item 2, whole building methods that use monthly or annual data do not account for the hours per day the building is used or how much equipment is inside the building. Even with detailed site visits NBI found that certain building characteristics, such as plug load magnitude and schedule, were very difficult to ascertain. Short-interval system-level data in theory can yield information about occupant schedule, amount of equipment and lighting, and overall what kinds of loads are in the building. This data can be used for classification to ensure one is comparing "like-type" buildings when using whole-building analysis methods.

When looking at system-level KPIs NBI focused on ensuring that they could be benchmarked against other buildings, data sets, or compared against historical performance. We sought to limit the detail of these KPIs to avoid replicating the functionality of more complex Energy Management Information Systems (EMS) that provide day-to-day feedback to building operators, or occupant dashboards. EMS systems have greater flexibility to address individual building needs and we wanted the KPIs to cut across buildings as well as serve in the absence of, or employed by these platforms in addition to their highly specialized calculations. To this end this KPI analysis does not intend to preclude more detailed metering for the purpose of facility operational maintenance, such as tracking chiller performance in kW/ton. Figure 1 depicts where the system KPIs protocols are intended to fall in a spectrum of commercial building data feedback analysis levels and detail.

Figure 1. A Graphic of NBI Analysis as Building Data Becomes More Detailed
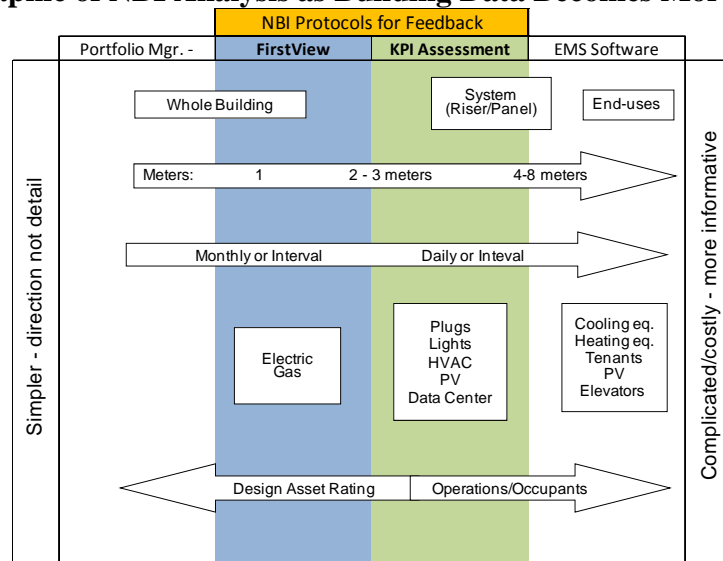
The KPI work began in Fall/Winter of 2010 and NBI conducted analysis and reporting through August of 2011. This report begins with a description of the project sites. Follows with a discussion of the system definitions used in the project. We then present results showing certain suggested numeric and graphical Designer KPIs for each site and then present conclusions based on the data for each site along with general findings.

Project Sites for KPI Development

Oakland Office

The Oakland office building is a 14,000 SF, two-story, LEED Platinum, renovation of an existing building with a single owner/occupant. The building uses 3 gas-pack/DX Packaged Rooftop Units (PRTU) and one DX-only PRTU in a one-per-zone configuration with a Reliable Controls Building Automation System (BAS). Thermofusers™ manage zone balancing. Demand controlled ventilation (DCV) is enabled through a sensor in the return air and in the conference room. The building uses gas for the Service Hot Water (SHW) and space heating system. The building envelope was designed for daylight and the lighting system, which is controlled by manual zonal switches, has embedded daylight sensors that switch certain lights completely off when sufficient daylight exists. The plug loads are typical office equipment and there is a large meeting space on the ground floor for public assembly. There is a server closet on the second floor. The building includes a 5.5kW nameplate PV system connected to the main distribution panel. System usage data was collected using a Northwrite data acquisition system with WattNode pulse-output meters recording data at 15-minute intervals. Observation took place from late 2010 through Sept 2011.

Vancouver Office

The Vancouver office is a 5,500 SF, single-story building occupied by a single tenant. The building has two gas-pack/DX PRTUs in a one-per-zone configuration. The thermostats are wireless and use a web-based interface that allows global control settings. A single conference room sensor provides DCV. The building uses gas for heating only and electric for all other end uses including SHW. The building is masonry with a wood frame ceiling and four skylights in the main open office area. The lighting system uses manual zonal switches with no active daylight controls. The ceiling height is above average at approximately 15 feet. The plug loads typical office equipment and the site has a small server closet. System data was collected using a Powermand data acquisition system and a Dent Powerscout 6-channel meter recording data at 90-second intervals. Observation took place from October 2010 through September 2011.

System Level Metering, Capabilities, and Definitions

Figure 2 shows a diagram of the system meter points NBI used in this project and recommended as a starting point for future discussion. Below the figure are sections with a discussion of each point. As a reminder this level of analysis does not seek to preclude more detailed metering, such as chiller kW per ton, but serve as a framework for defining the system level as the next level of detail past whole building.

In Figure 2 the dashed lines indicate a meter point that would most likely be "virtual", meaning that the reading is found by addition or subtraction of other physically metered points. In Figure 2 "WB" refers to Whole Building.

Figure 2. NBI System Diagram for the Two Sites
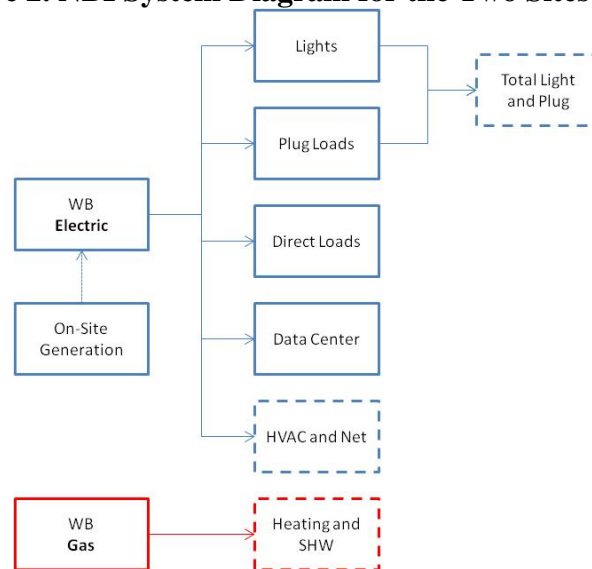
Today nearly all off-the-shelf electrical sub-meters, and many utility meters, are capable of storing or transmitting usage at least once per hour, thereby providing interval data as part of an Energy Information System,[NBI 2009], [PNNL 2005]. In addition Advanced Metering Infrastructure investments are increasing whole building interval data availability for gas and

electricity. The analysis in this paper requires least hourly interval data for electricity at whole building and all system meters. Whole building gas may or may not be interval data.

Whole Building Electricity

The whole building electric measurement included all the building and immediate site related electrical energy use. The whole building energy use should include the consumption of renewable energy to ensure that the KPIs account for all site energy consumption and is discussed in some detail in NREL publications [Torcellini et al 2006]

Only the Oakland office site included renewable energy generation in the form of 5.5kW of Photovoltaic panels. This was metered to arrive at the proper whole building electrical usage at each interval.

Lighting Electricity

The lighting energy is ideally the total facility <u>internal</u> lighting energy that serves the occupants excluding common area, exterior lighting, and any retail lighting. The purpose of limiting the definition to internal lighting serving occupants allows for a more direct measurement of the occupant's direct lighting needs and excludes lights that relate more to the operator's, or owner's, responsibility.

In small commercial buildings with a single tenant/occupant the distinction between internal and external/common is unlikely to be achievable and indeed this was the case with the two KPI sites where the lighting definition includes all lights on separated lighting panel. In larger buildings the electrical distribution is often subdivided for common area/core area lighting and/or egress emergency lighting or "Back of House" lighting. This can make it easier to divide the lighting to measure internal occupant lighting energy and allow the remainder to be included in HVAC and Net Electric described below.

Plug Load Electricity

In our analysis we rely heavily on the plug load to infer the behavior of occupants and similar to the lighting system it appears advantageous to define plug loads as those used by occupants only. The inclusion of possible large common area loads such as white goods (laundry and central kitchen equipment), auxiliary heating, unmetered common area retail space, will reduce the usefulness of the feedback and obscure the occupant schedule.

As with the lighting system since the two projects studied were small and plug loads from all areas were included in the definition. Both sites included a small server closet and the Oakland site used a temporary auxiliary 1.0 kW cooling system to augment the central HVAC system though the AC unit did not reject heat outside the building.

Data Center and Direct Load Electricity

Data centers of various sizes represent a rapidly growing source of electricity use [Koomey 2008] and there is extensive activity regarding performance metrics for data centers [EPA 2012]. NBI feels that when data centers are large, centralized, and have dedicated cooling via split HVAC systems that the data center and its accompanying HVAC system should be

metered in total as a separate system. Neither of the KPI sites had a data center installation that needed sub-metering by the definition above. Both sites did have server closets and the electricity use of these was included in the plug load system.

Direct load electricity represents an auxiliary category that could capture electric usage in buildings of very unusual use-types or mixed-mode situations like first floor retail, upper floor tenant space. This "system" may include plugs and lights, as well as HVAC if the situation warrants. The purpose of segregating this energy usage would be to assess its impact on the overall building energy use and provide feedback to the third-party entity responsible for its management. There may be other building use types where this applies more frequently though this is outside the scope of this paper.

HVAC and Net Electricity

HVAC and Net Electric is the remainder of electrical energy usage once plug loads, lighting, data center, and direct loads are totaled and subtracted from the whole building electrical use. This system includes all components used in the HVAC system, miscellaneous pumps, elevators, and even common area lighting and plug loads that do not fall into the two categories above. The broadness of this system definition is deliberate for these sites, and to anticipate others especially existing buildings, where components of the HVAC system are distributed widely or are too numerous to meter in a handful of meter points. Both KPI sites were small offices with packaged rooftop equipment and relatively little common areas and so had relatively similar HVAC and Net electrical definitions.

Whole Building Gas

This system consists of the whole building gas or other fuel, preferably with interval data, consumed at the building or site as defined by the Whole Building Electric system. NBI intended to acquire gas interval data at each site but were not able due to the specification of the utility meter and time constraints and so both sites used monthly utility meter gas data for the KPI development.

Design: Metered KPIs

The KPIs derived here try to answer questions that designers have regarding the building. For example a designer would like to know how much energy resulted from the building design choices versus the operator or occupant impact, or how well specified approaches for lighting, HVAC, or envelope performed. This feedback must remain high level and look over a longer time, like a full year of activity, to ensure the building has gone through heating and cooling seasons but still leverage the detail of the interval data to enhance findings based on time-of-use with rolled up annual numbers.

These KPIs are like any other numerical calculation of energy usage in that they are usually only useful when placed in context of comparisons to expected or historical behavior. Broadly these comparisons are: (1) a large data set of similar buildings – benchmarking, (2) a private portfolio of similar buildings, (3) historical data, and (4) design model expectations. We provide comparisons when data exists but this project seeks to explore a framework that hopefully will eventually have more data for comparisons.

The **Schedule Visualized EUI** is an indicator that quickly assesses the EUI contribution of each system while also examining the number of hours per typical workday across a year that the system represents an "active" status implying a schedule of use. The determination of active status is made through a simple algorithm for active vs. inactive [Hart et al 2004] based on hourly deviation from a baseline condition for plug loads on non-holiday weekdays.

Figure 3 shows the Schedule Visualized EUIs (in kBTU/SF/yr) for the Vancouver and Oakland offices. Figure 3 is a stacked chart where the EUI of each system type is stacked on top until the total annual EUI is reached at the top. Then the active hours of each system type are shown on the x-axis.

Figure 3. The Schedule Visualized EUI Indicator
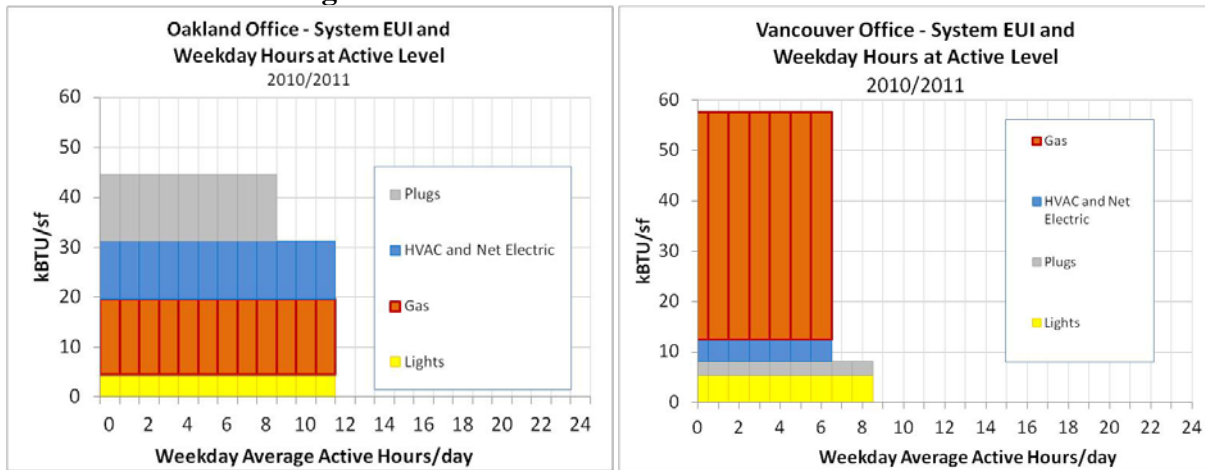
Note that the overall area of each system does not directly convert to energy usage only the height on y-axis which represents the contribution to EUI and the width on the x-axis which represent the average active hours. We are exploring other graphical representations.

Figure 3 shows that for Oakland the building may be occupied 12 hours per day, though the plug load schedule infers that there is significant use only 8 hours per day. One can see that even though the lighting has a longer schedule the plug load is significantly larger. It is difficult to say if any aspect of the building energy is unusual without comparisons but the designer can get a quick feel for how the building uses energy. Comparisons of EUI are possible to national or state survey data but the problem of misaligned system definitions made this difficult.

In the absence of more detailed data plug loads are an important indicator as a proxy for occupancy either as a test of variation of occupancy in a given year or an assessment of occupant electric load magnitude. A designer should want to know if the performance data for a particular building is from a year with stable or partial occupancy and also how the rest of the building performed in light of how much equipment the occupants used. In the first question NBI used data on the intensity and schedule of the plug load to assess the stability of occupancy data for each site as shown in Figure 4. This was used to make a qualitative assessment of the occupancy of the building called the **Occupancy Consistency Indicator**.

Lighting loads may also be considered a proxy for occupancy though as was seen in the Oakland case the building was regularly used after hours without significant plug load use that goes with "regular" office workers. In addition after hours cleaning often results in a lot of lighting use with very little actual occupancy. Lastly many buildings are controlled by master sweep systems that do not reflect the actions and schedule of occupants themselves.

Figure 4 shows monthly data where the diamonds are the average energy use rate density (in W/SF) plotted with the squares that are average weekday active plug load schedule hours (on the right Y-axis) each month for the site. The x-axis is the average outdoor temperature in the month. The Oakland office was assessed qualitatively by inspection as "Moderately Stable" while the Vancouver office was assessed as "Stable". These are somewhat arbitrary assessments but the point is to assure the designer of what happened to occupancy during the year. More data for comparison will help define these terms with greater consistency.

Figure 4. Data for the Occupancy Consistency Indicator
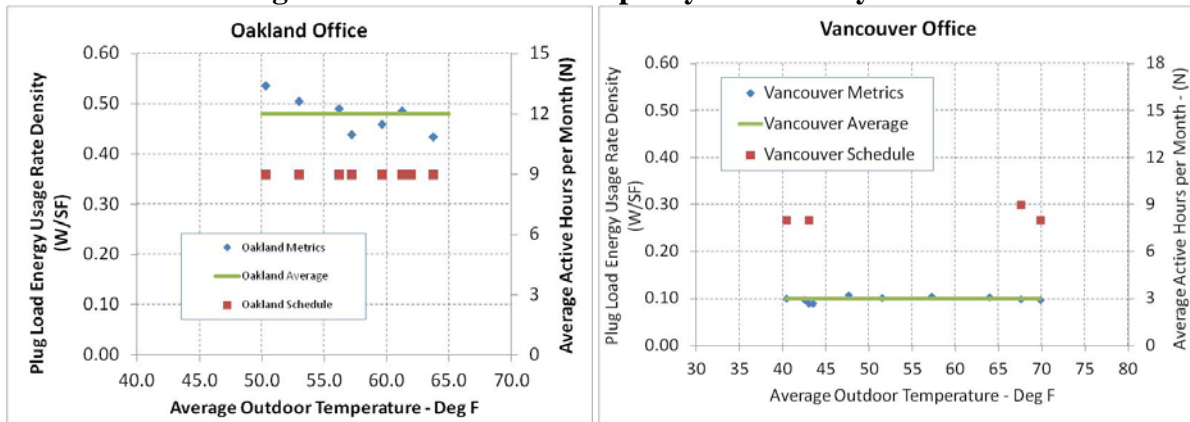
The magnitude of occupants use energy via plug loads can be expressed through metrics of performance to indicate the how the occupants are using energy relative to similar buildings. The designer or owner can use this more detailed look at occupancy usage to assess the success of the overall building energy usage in terms of these occupant choices but also in comparing "like-type" buildings, i.e. ones with similar occupant usage (This could also potentially include lighting usage) to assess other systems effectiveness.

The **Occupant Usage Indicator** uses metrics of performance using protocols developed for the Office of the Future (OTF) project which created standard metrics to define energy performance for use in comparing office energy use over 16 sites and several years. Since these building were both used as offices NBI had data from that project to create benchmark comparisons. Table 1 shows the annual metrics for each office and some benchmarked comparison data from the OTF sites and research sources including a median performance case and a "High Performance" (i.e. low energy) case.

Table 1. Data for the Occupant Usage Indicator

Plug Load Metric	Unit	Oakland Office	Vancouver Office	High Performance Case	Median Case
Occ. Energy Use Rate Density	W/SF	0.62	0.15	0.12	0.55
Peak Energy Use Rate Density	W/SF	1.01	0.45	0.39	0.86
Workday Energy Use Rate Density	W/SF	0.48	0.11	0.10	0.41
Off Hours Ratio	-	70%	48%	39%	59%
Weekend Ratio	-	78%	55%	50%	70%
Occupant Usage Assessment	**-**	**High**	**Very Low**		

The Occupied Energy Use Rate Density is a measure of the average energy use rate density (in W/SF) between the hours of 6:00AM and 6:00PM on non-holiday weekdays. The Peak Energy Use Rate Density is the highest W/SF in a single interval during the year. The Workday Energy Usage Rate Density is the average 24-hour W/SF for non-holiday weekdays. The Off Hours Ratio compares average energy use in the non-occupied time versus the occupied hours and the Weekend Ratio compares 24-hour average energy use on non-holiday weekdays to average usage in Saturdays, Sundays, and Holidays.

The data show that the Oakland office occupant uses more than the median case in all metrics. Particularly notable is the Off Hours and Weekend Ratios. The designer can infer that the occupant is partially responsible for increased energy usage and even determine about how much against the comparison case. The next project can strive to enable occupant feedback or plug load measures to drive this downwards. The Vancouver office shows very low usage.

NBI found a simple indicator that provides a high level comparison for design and operations as opposed to occupant behavior with buildings of similar climate zones and ideally from similar years. The **Design and Operations vs. Occupants Indicator** compares the combined plug load and lighting systems EUI against the HVAC and Net Electric plus Whole Building Gas usage. The intention was to draw a distinction between energy used by occupant activities compared to the amount of energy used to operate the building that supports the occupants. As a fundamental driver of performance the amount of energy used to support occupant activities should be as small as possible.

In an ideal case the ratio would be zero, meaning that the building used no additional energy outside what the occupants needed to perform their productive work. Since the ideal is rarely the case, some method of benchmarking the measured results varies is needed.

Table 2. Comparison Data for the Design and Operations vs Occupant Indicator

Building	2010/2011 Design-Occupant Indicator	NBI Data Average	NBI Data Std. Dev	NBI Data Maximum	NBI Data Minimum
Vancouver Office	6.07	2.09	0.72	2.76	0.98
Oakland Office	1.49	1.53	0.77	3.05	0.41

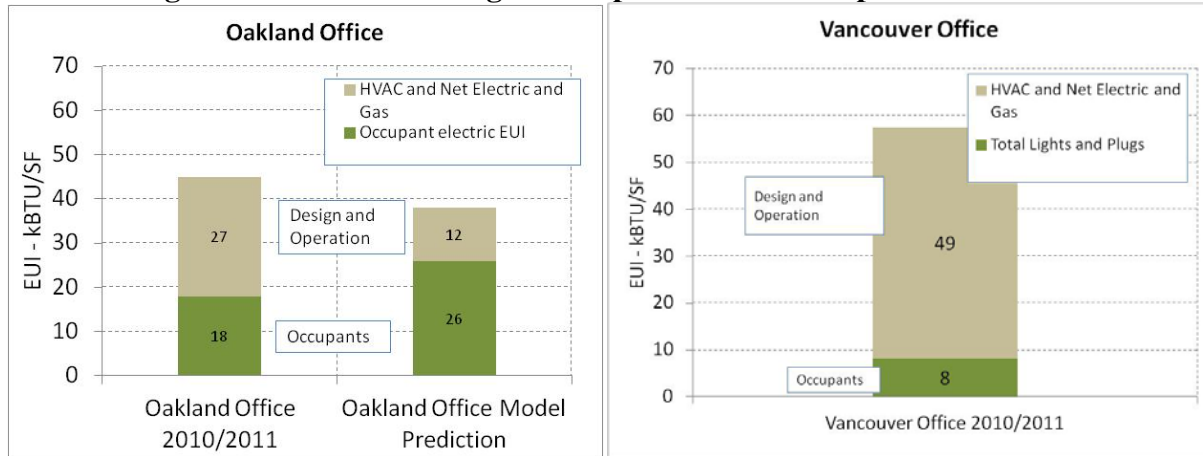**Figure 5. Plots of the Design and Operations vs Occupants Indicators**

Table 2 shows the results for Oakland and Vancouver along with data from the NBI database taken from offices with a similar occupant (internal gain) EUI for a similar climate zone. The large standard deviation shows the need for a larger data set. Despite the wide range the Vancouver office is clearly a poor performer. The Oakland office is of average performance though design model data was available for the building and shows that not only was the overall EUI prediction not accurate the occupant usage assumptions were incorrect.

Metrics of the energy performance of the lighting system can reveal how the lighting energy usage responds to daylight levels. The lighting system energy use should be impacted by daylight choices made by the design team either through the inclusion of daylight design in the envelope, causing occupants to manually respond to light or through the use of lighting controls that automatically respond to daylight, or both.

Figure 6 shows a plot of the metrics of the **Daylight Effectiveness Indicator**. This is a more expressive demonstration of the correlation between the monthly Occupied Energy Use Rate Density for lighting and night lengths in hours co-plotted versus time. One can clearly see that in the Oakland office the lighting energy use responds to daylight where in the Vancouver office the response is muted. This behavior implies that the lighting design characteristics in Oakland are superior to Vancouver.

Figure 6. Data for the Daylight Effectiveness Indicator
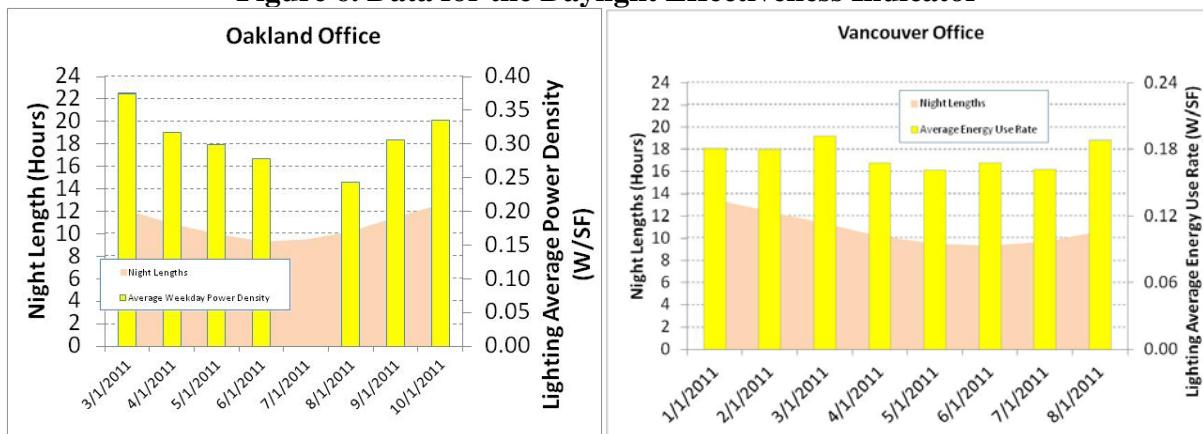
Further examination of the lighting data through OTF metrics led to an **Overall Lighting Performance Indicator** which is useful to compare actual energy performance across platforms. The designer can use this assessment to determine the field effectiveness of the occupant-serving lighting system compared to other lighting systems or strategies for like-type buildings, particularly taking into account occupancy related indicators and envelope design choices. Comparisons to the OTF data led to a qualitative comparison of lighting performance shown in Table 3.

Table 3. Data for the Overall Lighting Performance Indicator

Lighting Load Metric	Unit	Oakland Office	Vancouver Office	High Performance Case	Median Case
Design Installed Lighting Capacity	W/SF	0.81	~1.0	N/A	N/A
Peak Energy Use Rate Density	W/SF	0.74	0.56	0.29	0.71
Occ. Energy Use Rate Density	W/SF	0.33	0.30	0.18	0.39
Occupant Usage Assessment	**-**	**Median**	**Median**		

For the HVAC system NBI uses the HVAC and Net Electric system data in two ways. The **HVAC and Net Electric Baseload Indicator** is a numerical value based on the monthly energy signature [LBNL 2011] of the building shown as the dark blue line and diamonds in Figure 7. The signature represents the common area loads which are typically stable throughout the year and the increased fan energy in the winter (left side) as well as the increased fan and DX usage in the summer (right side). The value of the baseload or lowest point (0.28 W/SF in Oakland and 0.08 W/SF in Vancouver) is a valuable indicator of size of the common area contribution and the potential overlap in heating and cooling caused by poor operating conditions. Unfortunately we had only these two buildings to compare.

As a complement to the baseload indicator NBI examined the **Operational Consistency Indicator** by looking at the HVAC and Net electric energy signature in monthly and weekly increments for an indication of whether the building HVAC system is well controlled. Figure 7 shows this as the hollow squares plotted over the monthly signature of the blue line. Note how the Vancouver office co-plots well while the Oakland office is very erratic. This implies that control related issues might be contributing to poor operating conditions in Oakland.

Figure 7. Data for the Operational Indicators
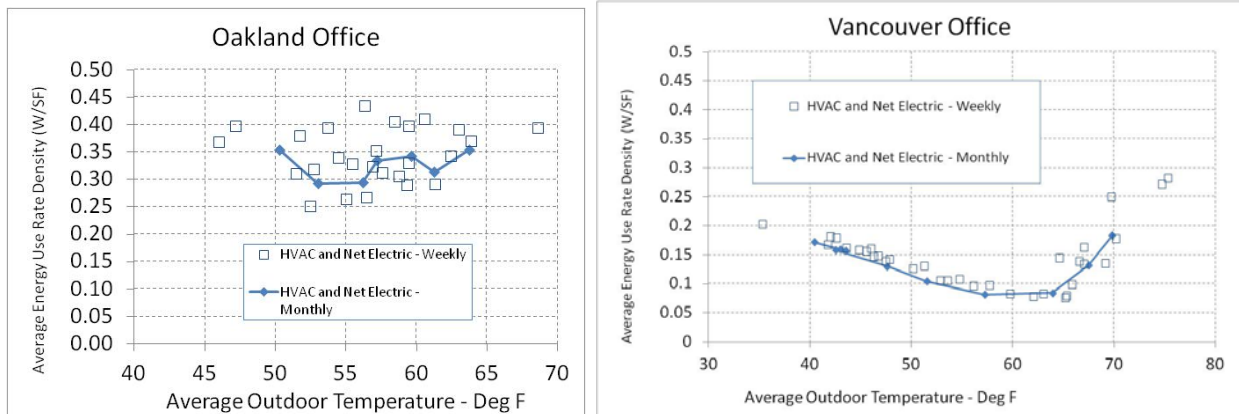
CONCLUSIONS

We identified certain system meter based KPIs for Designers, Operators, and Occupants that can interpret performance in a commercial building at a broad level and potentially provide a basis for system level benchmarking in the future. Table 4 summarizes the indicator conclusions.

Table 4. Final Summary of Selected Designer KPIs and Assessments for Each Site

Design KPI	Oakland Assessment	Vancouver Assessment	Comparison Set
Schedule Normalized EUI	-	-	-
Occupancy	Moderately Stable	Stable	Inspection
Occupant Usage	High	Very Low	NBI data
Design and Operations vs. Occupant	Average (Poor - design model)	Very High	Design data, NBI data
Daylight Effectiveness	Excellent	Poor	Inspection
Overall Lighting Performance	Median	Median	NBI data
HVAC and Net Electric Baseload	0.28 W/SF	0.08 W/SF	Reciprocal
Operational Consistency	Erratic	Stable	Inspection

Both buildings were small and both were office buildings. These limitations hinder the ability to make broader conclusions of the KPI efficacy but made a good side-by-side case study.

The KPIs show that the Oakland office had stable occupancy and high occupant loads that may have contributed to inaccurate design assumptions resulting in a higher Design and Operations v. Occupants ratio. The daylight controls appeared to be very effective though the occupancy was not perfectly stable. The designer may want to consider the HVAC and Net Electric Baseload and Operational Consistency more closely before making a determination on the overall performance of the building relative to the design choices. These indicators suggest the operations may be impacting the overall EUI.

In Vancouver there is a clear problem with gas usage despite the schedule of the building appearing to be "normal", i.e. around 8 hours per day. This could be due to the very low plug loads which augment heating but the magnitude of gas use is very high. The HVAC and Net Electric Baseload and Operational Consistency indicators appeared to be reasonable leading to the suggestion that the envelope may be more responsible for the heating issues than poor operation.

NBI found that system level metering is a complex technical and definitional problem that must be closely coordinated with codes and standards, design and construction professionals, and energy analysts to establish a well defined set of what is included in each system so that and metered KPI methodology can be easily and repeatedly accomplished in the field. The system level definitions should be cognizant of the building stock, the variations of fuel distribution, building modifications, metering capabilities, and enhanced benchmarking tools like FirstView.

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