THE BULLITT CENTER EXPERIENCE: MODELING AND MEASURING NET ZERO ENERGY

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ABSTRACT

This paper discusses energy use in the Bullitt Center, a 50,000 sf 6-story office building in Seattle, WA designed to achieve net-zero energy performance.

The paper will discuss design phase energy modeling, actual metered energy use, and provide comparisons between the modeled and actual data. Actual data is from the first year of energy metering, beginning January 2014. The data set is a partial year, likely January through October 2014, and will represent the building's early performance during a "tuning" period of the building's systems.

To meet the Living Building Challenge, the building was designed to the highest degree of energy efficiency and was provided with a photovoltaic (PV) powerplant to produce as much energy annually as the building is predicted to use. Significant effort was put into design-phase modeling of the proposed building's energy use and comfort to account for all of the energy needed to operate and occupy the building. The paper discusses the assumptions related to envelope, usage schedules, internal equipment loads, and mechanical and electrical systems including lighting and PV.

The building is equipped with electrical submetering equipment to aggregate energy use into categories of plug loads, lighting, mechanical, water heating, elevator, and IT. The paper discusses the trends and patterns seen in the building's first year of data collection. Both energy and comfort parameters are explored.

A comparison between the modeled and metered data is presented for the building. Differences between the data sets are explored in the paper and an analysis of potential causes of divergence will be discussed. The focus of the discussion is in what the divergence suggests about modifying the buildings control strategies.

INTRODUCTION

The Bullitt Center is a 51,000 ft^2, six-story speculative office building built in Seattle, WA. Construction was completed in February 2013, where upon tenants began to immediately occupy the building (The first tenants moved in late February/March and the building was officially opened on earth day April 22nd, 2013). The building was designed to meet the requirements of the Living Building Challenge (LBC) version 2.0; these requirements include net zero energy use, which is defined as generating 100% of the project's energy needs by on-site renewable energy on a net annual basis.

To meet the Living Building Challenge, the building was designed to the highest degree of energy efficiency and was provided with a 242 kW photovoltaic (PV) powerplant to produce as much energy annually as the building is predicted to use. Significant effort was put into design-phase modeling of the proposed building's energy use and comfort to account for all of the energy needed to operate and occupy the building.

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The paper presents the modeling tools and assumptions, and operational data for the past year's operation and presents a comparison and analysis of the results.

MODELING METHODS

The analyses used a computer model of the building created using the DOE2 energy analysis software. DOE2 performs hourly calculations for 8,760 hours per year using hourly weather data. The information in the following is a summary of the assumptions regarding the building geometry, internal loads and HVAC systems used to develop the annual energy use simulations.

Weather Data

Weather data for Seattle, WA is used in the analyses.

Architectural Assumptions

Table 1 summarizes the spaces modeled and total square footage of each space type.

Space Type	Area (ft2)
Office Space	31,314
Rest Rooms	2,365
Corridor	4,104
Stair	3,722
Mechanical/Electrical	3,434
Elevator	568
Storage	1,203
Compost	1,747
Cistern	804
Sun Room	810
Total	50,071

Table 1: Space Use

Building Massing

The model was created to match the final configuration of the Bullitt Center to within a 5% difference of any façade elements. Shading elements were included to capture the effects of nearby structures and vegetation. Vegetation was modeled to change its shading parameters seasonally. Figure 1 illustrates renderings of the building geometry coded into DOE2.

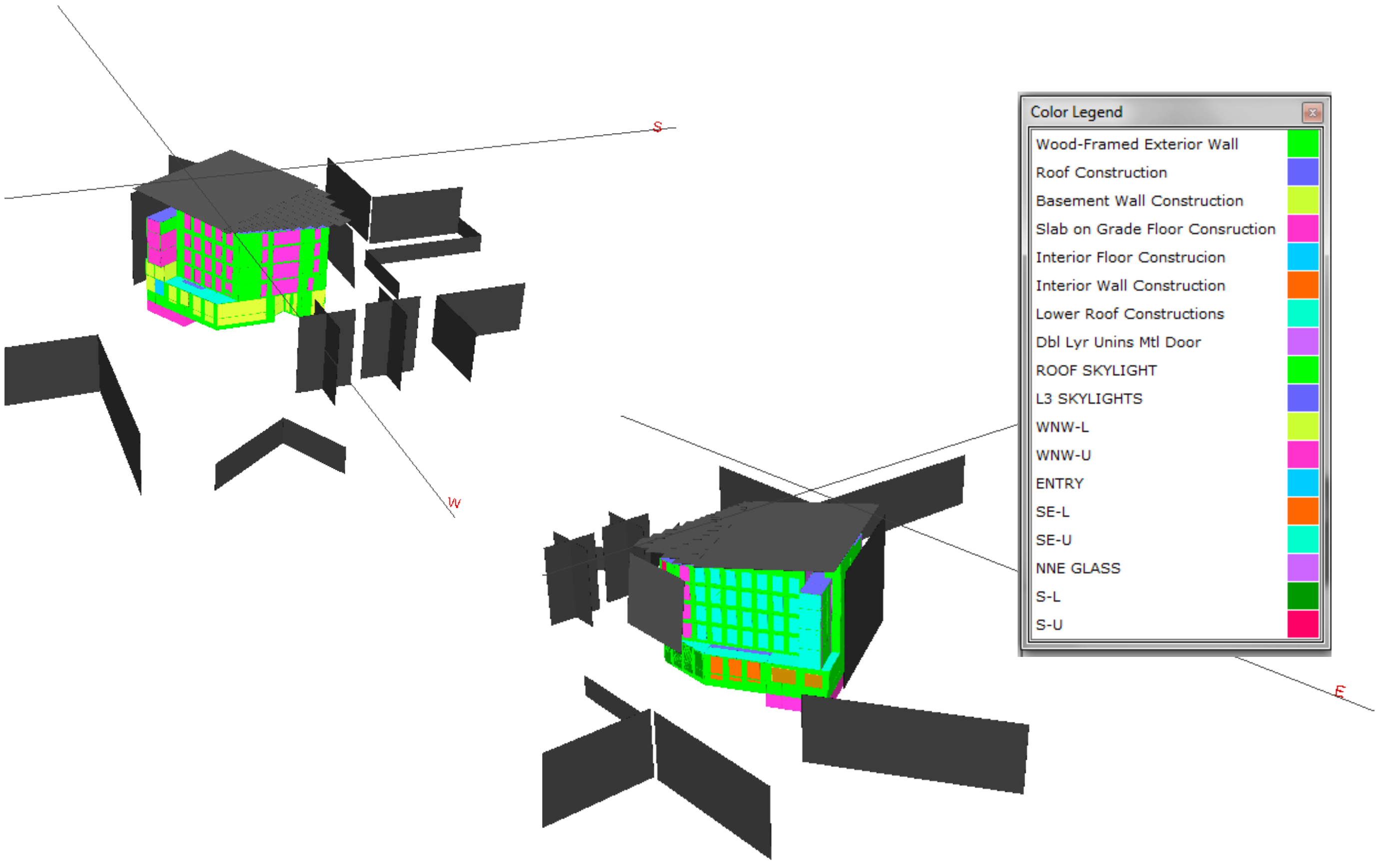


Figure 1: Rendering of DOE2 Input

Envelope Components

The building's envelope was designed to significantly surpass the requirements of the building codes and standards at the time of permitting. Table 2 summarizes the envelope parameters in the Bullitt Center's final model and construction. The model and construction values differ due to changes made after the final energy model completion.

Category	Seattle Energy Code 2009	ASHRAE 90.1-2010 Appendix G	Bullitt Center As Modeled	Bullitt Center As Built
Exterior Wall Construction	Overall U-Factor = 0.055, R = 18.2 (Non-Residential)	Overall U-Factor = 0.064, R = 8 (Non-Residential, Steel Framed)	Overall U-Factor = 0.047, R = 21.4 Metal Siding Air Space 4" Mineral Wool 5/8" Glass Mat Gypsum Sheathing 6" Metal Studs with R-19 Insulation Gypsum Wall Board	Overall U-Factor = 0.038, R = 26.3

Roof Construction	Overall U-Factor = 0.026, R = 38 (Non-Residential)	Overall U-Factor = 0.048, R = 15 (Non-Residential Insulation above deck)	Overall U-Factor = 0.026, R = 38	Overall U-Factor = 0.025, R = 40
<u>Windows</u> All	<u>0-30% Glazing</u> Assembly U-value = 0.38, R = 2.6 Solar Heat Gain Coefficient (SHGC) = 0.35	<u>0-40% Glazing (Metal Framing)</u> Assembly U-value (Curtain Wall/Storefront) = 0.5, R = 1.8 Assembly U-value (Other) = 0.55 Solar Heat Gain Coefficient (SHGC) = 0.4	<u>37% Glazing</u> <u>Curtain Wall (Levels 1 and 2)</u> Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.43 Visible Transmittance = 0.53 <u>Windows (Levels 3 through 6)</u> *PPG Sungate 500* Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.43 Visible Transmittance = 0.53	<u>37% Glazing</u> <u>Curtain Wall (Levels 1 and 2)</u> Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.31 Visible Transmittance = 0.51 <u>Windows (Levels 3 through 6)</u> *PPG Sungate 500* Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.31 Visible Transmittance = 0.51
<u>Windows</u> Greenhouse	<u>0-30% Glazing</u> Assembly U-value = 0.38, R = 2.6 Solar Heat Gain Coefficient (SHGC) = 0.35	<u>0-40% Glazing (Metal Framing)</u> - Assembly U-value (Curtain Wall/Storefront) = 0.5, R = 1.8 Assembly U-value (Other) = 0.55 Solar Heat Gain Coefficient (SHGC) = 0.4	<u>All Levels</u> *PPG Sungate 500* Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.43 Visible Transmittance = 0.53	<u>All Levels</u> *PPG Sungate 500* Assembly U-value = 0.25, R = 4 Solar Heat Gain Coefficient (SHGC) = 0.31 Visible Transmittance = 0.51

Skylights	<u>0-30% Glazing</u> Assembly U-value = 0.55, R = 1.8 Solar Heat Gain Coefficient (SHGC) = 0.32	<u>0-40% Glazing (Metal Framing)</u> Assembly U-value = 1.17, R = 0.855 Solar Heat Gain Coefficient (SHGC) = 0.49	<u>Level 3</u> Assembly U-value = 0.25 , R = 4 Solar Heat Gain Coefficient (SHGC) = 0.28 Visible Transmittance = 0.48 <u>Roof</u> Assembly U-value = 0.20 , R = 5 Solar Heat Gain Coefficient (SHGC) = 0.28 Visible Transmittance = 0.48	<u>Level 3</u> Assembly U-value = 0.25 , R = 4 Solar Heat Gain Coefficient (SHGC) = 0.28 Visible Transmittance = 0.48 <u>Roof</u> Assembly U-value = 0.20 , R = 5 Solar Heat Gain Coefficient (SHGC) = 0.28 Visible Transmittance = 0.48
Infiltration	0.4 cfm/sqft(of wall) at 75 Pa	Not Regulated	0.24 cfm/sqft(of wall) at 75 Pa	0.19 cfm/sqft(of wall) at 75 Pa
Orientation		Average of four 90° rotations	As designed	As designed

Table 2: Building Envelope Parameters

Internal Load Patterns

The building will operate all days of the week. Daily schedules of operation will vary with different space types.

Occupancy. Heat gains resulting from people were modeled in the simulations. The heat gain per person is estimated as 250 Btu/h sensible and 200 Btu/h latent in all areas (ASHRAE Fundamentals, 2005). The number of occupants and the occupancy schedules in the energy analysis are listed below by function. Table 3 summarizes the assumed maximum occupancy densities for each space-type. Figures 2 and 3 summarize the assumed occupancy patterns.

Space Type	Area Person (sqft/person)	Basis
Office Space	150	Discussion with Architect
Conference Room	20	ASHRAE - Conference
Lobby	30	ASHRAE - Lobby
Other Spaces	Not regularly occupied	

Table 3: Maximum Occupancy Densities

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	0%	0%	0%	15%	30%	30%	30%	15%	10%	10%	10%	10%	5%	5%	0%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	5%	10%	20%	80%	80%	80%	80%	50%	80%	80%	80%	80%	60%	40%	20%	10%	10%	5%	5%
T	0%	0%	0%	0%	0%	5%	10%	20%	80%	80%	80%	80%	50%	80%	80%	80%	80%	60%	40%	20%	10%	10%	5%	5%
W	0%	0%	0%	0%	0%	5%	10%	20%	80%	80%	80%	80%	50%	80%	80%	80%	80%	60%	40%	20%	10%	10%	5%	5%
T	0%	0%	0%	0%	0%	5%	10%	20%	80%	80%	80%	80%	50%	80%	80%	80%	80%	60%	40%	20%	10%	10%	5%	5%
F	0%	0%	0%	0%	0%	5%	10%	20%	80%	80%	80%	80%	50%	80%	80%	80%	80%	60%	40%	20%	10%	10%	5%	5%
S	0%	0%	0%	0%	0%	0%	0%	0%	15%	30%	30%	30%	15%	10%	10%	10%	10%	5%	5%	0%	0%	0%	0%	0%

Figure 2: Occupancy (Office)

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	50%	90%	90%	50%	25%	0%	0%	0%
M	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	25%	80%	25%	80%	80%	25%	80%	80%	25%	25%	10%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	25%	80%	25%	80%	80%	25%	80%	80%	25%	25%	10%	0%	0%	0%
W	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	25%	80%	25%	80%	80%	25%	80%	80%	25%	25%	10%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	25%	80%	25%	80%	80%	25%	80%	80%	25%	25%	10%	0%	0%	0%
F	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	25%	80%	25%	80%	80%	25%	80%	80%	25%	25%	10%	0%	0%	0%
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 3: Occupancy (Conference)

Lighting. Lighting power densities are based on the proposed targets generated by the design team. The majority of the building is being built as core-and-shell for later tenant fit out. As such, the lighting power densities assumed represent lighting power budgets based on a feasible tenant lighting layout. The design includes photo-cell controlled task lighting for workstations within both the 15' perimeter zone, and workstations within 30' of the perimeter. Ambient lights are also assumed to be photocell controlled.

Table 4 summarizes the proposed lighting power densities and allowed ASHRAE 90.1-2004 densities. Figures 4 through 8 illustrate the assumed lighting schedules before daylight dimming, but with occupancy sensor control.

Space Type	Lighting Power Density (W/ft^2)		
	Seattle Energy Code	ASHRAE 90.1 2010 Appendix G	Proposed Building
Office	0.9	0.98	0.4
Conference	0.9	1.23	0.9
Restroom	0.9	0.98	0.45
Mechanical Room	0.9	0.95	0.69
Back of House MEP	0.9	0.95	0.34
Parking	0.9	0.19	0.28
Sun Room	0.9	0.73	0.28
Stairs	0.9	0.69	0.29

Table 4: Lighting Power Densities

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	33%	33%	43%	53%	53%	53%	43%	40%	40%	40%	40%	36%	36%	0%	0%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	40%	46%	87%	87%	87%	87%	67%	87%	87%	87%	87%	73%	60%	46%	40%	40%	36%	36%	0%
T	0%	0%	0%	0%	0%	40%	46%	87%	87%	87%	87%	67%	87%	87%	87%	87%	73%	60%	46%	40%	40%	36%	36%	0%
W	0%	0%	0%	0%	0%	40%	46%	87%	87%	87%	87%	67%	87%	87%	87%	87%	73%	60%	46%	40%	40%	36%	36%	0%
T	0%	0%	0%	0%	0%	40%	46%	87%	87%	87%	87%	67%	87%	87%	87%	87%	73%	60%	46%	40%	40%	36%	36%	0%
F	0%	0%	0%	0%	0%	40%	46%	87%	87%	87%	87%	67%	87%	87%	87%	87%	73%	60%	46%	40%	40%	36%	36%	0%
S	0%	0%	0%	0%	0%	33%	33%	43%	53%	53%	53%	43%	40%	40%	40%	40%	36%	36%	0%	0%	0%	0%	0%	0%

Figure 4: Lighting (Office)

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	50%	50%	50%	50%	50%	50%	50%	50%	50%	63%	75%	95%	95%	75%	63%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	50%	50%	90%	90%	63%	90%	63%	90%	90%	63%	90%	90%	63%	63%	80%	75%	0%	0%	0%
T	0%	0%	0%	0%	0%	50%	50%	90%	90%	63%	90%	63%	90%	90%	63%	90%	90%	63%	63%	80%	75%	0%	0%	0%
W	0%	0%	0%	0%	0%	50%	50%	90%	90%	63%	90%	63%	90%	90%	63%	90%	90%	63%	63%	80%	75%	0%	0%	0%
T	0%	0%	0%	0%	0%	50%	50%	90%	90%	63%	90%	63%	90%	90%	63%	90%	90%	63%	63%	80%	75%	0%	0%	0%
F	0%	0%	0%	0%	0%	50%	50%	90%	90%	63%	90%	63%	90%	90%	63%	90%	90%	63%	63%	80%	75%	0%	0%	0%
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 5: Lighting (Conference)

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%
W	0%	0%	0%	0%	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%
F	0%	0%	0%	0%	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%	25%	0%	0%	0%	0%	0%	0%	0%
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 6: Lighting (Public Mechanical Space)

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	0%	0%	0%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	0%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	0%	0%	25%	90%	75%	75%	75%	90%	75%	75%	75%	90%	80%	75%	60%	30%	15%	8%	0%
T	0%	0%	0%	0%	0%	0%	0%	25%	90%	75%	75%	75%	90%	75%	75%	75%	90%	80%	75%	60%	30%	15%	8%	0%
W	0%	0%	0%	0%	0%	0%	0%	25%	90%	75%	75%	75%	90%	75%	75%	75%	90%	80%	75%	60%	30%	15%	8%	0%
T	0%	0%	0%	0%	0%	0%	0%	25%	90%	75%	75%	75%	90%	75%	75%	75%	90%	80%	75%	60%	30%	15%	8%	0%
F	0%	0%	0%	0%	0%	0%	0%	25%	90%	75%	75%	75%	90%	75%	75%	75%	90%	80%	75%	60%	30%	15%	8%	0%
S	0%	0%	0%	0%	0%	0%	0%	0%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	0%	0%	0%	0%	0%

Figure 7: Lighting (Parking Garage)

	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
M	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
W	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
T	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
F	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 8: Lighting (Back-of-house Mechanical Space)

Miscellaneous Equipment. Miscellaneous equipment power densities were assumed based on space-type and the anticipated equipment in each space. The following list summarizes the equipment assumed to establish the tenant energy budget. Each piece of equipment was assigned a specific usage schedule; the aggregated usage schedules were combined to create the overall plug-load schedule shown in Figure 9.

Office Equipment power is based on the following equipment assumptions:

1. 150 people/sqft.
2. 20% of people have a 40 Watt lap-top with one 22 W monitor.
3. 15% of people have a 20 Watt thin-client with one 25 W monitor.
4. 65% have one 51 Watt desktop station with two monitors at 22 W each.
5. Task lights are integrated into the ambient lighting system and included in the lighting energy budget.
6. One 1100 Watt copier per 20 people, used for 20 minutes of every hour during the workday
7. One Energy Star refrigerator per floor
8. One microwave per floor, used for 1.5 hours per day
9. One dishwasher per floor used for 2 cycles per day
10. One 250 Watt projector in the main conference room
11. Two 110 W 55” Flatscreen TV (Samsung UN55C8000 or similar) per floor
12. 15 Watts personal power allowance per person (cell charger, etc)
13. Phantom loads eliminated through occupancy sensor power strips and low power settings on equipment.
14. One ceiling ventilation fan per ~800 sf, running at medium speed about 15% of the time.

S	1%	1%	1%	1%	1%	1%	2%	2%	11%	17%	17%	17%	9%	9%	9%	9%	9%	5%	4%	2%	2%	2%	1%	1%
M	1%	1%	1%	1%	1%	3%	5%	11%	34%	34%	34%	38%	41%	38%	34%	34%	38%	28%	17%	8%	5%	5%	3%	3%
T	1%	1%	1%	1%	1%	3%	5%	11%	34%	34%	34%	38%	41%	38%	34%	34%	38%	28%	17%	8%	5%	5%	3%	3%
W	1%	1%	1%	1%	1%	3%	5%	11%	34%	34%	34%	38%	41%	38%	34%	34%	38%	28%	17%	8%	5%	5%	3%	3%
T	1%	1%	1%	1%	1%	3%	5%	11%	34%	34%	34%	38%	41%	38%	34%	34%	38%	28%	17%	8%	5%	5%	3%	3%
F	1%	1%	1%	1%	1%	3%	5%	11%	34%	34%	34%	38%	41%	38%	34%	34%	38%	28%	17%	8%	5%	5%	3%	3%
S	1%	1%	1%	1%	1%	1%	2%	2%	11%	17%	17%	17%	9%	9%	9%	9%	9%	5%	4%	2%	2%	2%	1%	1%
	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11

Figure 9: Office Equipment Schedules

Additional Equipment Loads included in the proposed building:

1. All of the tenants’ servers are assumed to be located in the basement and first floor telecom rooms and require a combined maximum of 17,000 kWh energy annually (Miller Hull/PAE estimate).
2. The DDC system is assume to add 5 W per control point and the building is assumed to have one control point per 200 sqft, consuming approximately 1,500 kWh/year.
3. One regenerative elevator is assumed in the project, consuming 7,000 kWh/year.
4. The transformer vault fan designed to be 800 cfm, constant volume, and 0.25” of static pressure, consuming about 400 kWh/year.
5. Toilet waste composers have variable speed fans than cycle between 20 and 200 cfm depending on bathroom occupancy. The fans as assumed to consume 200 kWh/year.
6. Outside air supply and exhaust fans for conference rooms consume approximately 2200 kWh/year.
7. Foam flush toilets consume 4 W continuously and 8 W for 45 seconds when flushing. ~500 kWh/year.

8. The garage door opener is assumed to consume 8W continuously and 800 W for 10 seconds when opening (100 openings/day). ~150 kWh/year.

Interior Environmental Conditions

Heating and Cooling Seasons. Heating and cooling of the radiant floor are available as follows:

1. Heat is available from October 1 through April 30
2. Cooling is available from May 1 through September 30

Figures 10 and 11 illustrate the temperature schedules assumed in the model.

S	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
M	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
T	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
W	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
T	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
F	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
S	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11

Figure 10: Office Heat – Temp Setpoint °F

S	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
M	85	85	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	85	85	85	85	85	85	85
T	85	85	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	85	85	85	85	85	85	85
W	85	85	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	85	85	85	85	85	85	85
T	85	85	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	85	85	85	85	85	85	85
F	85	85	85	85	85	80	80	80	80	80	80	80	80	80	80	80	80	85	85	85	85	85	85	85
S	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
	M	1	2	3	4	5	6	7	8	9	10	11	N	1	2	3	4	5	6	7	8	9	10	11

Figure 11: Office Cooling – Temp Setpoint °F

Systems

Space conditioning is provided by a hybrid system consisting of closed loop geothermal system with water-to-water heat pumps serving radiant floor heating and cooling, conditioned ventilation air, and passive cooling and natural ventilation through operable windows.

Air-Side. Ventilation air is supplied by a dedicated outside air handling unit. The unit is equipped with the following:

1. Changeover hot/chilled water coil
2. Supply and return fans
3. 60% effective heat recovery wheel
4. MERV 13 filters
5. Variable speed drive for fans
6. Fan speed controlled based on CO2 readings

The following table summarizes the fan parameters of the dedicated outside air handling unit:

Air Handling Units										
ID	Supply Airflow (cfm)	Total SP (inches)	Supply Fan Efficiency	Fan BHP	Motor Efficiency	Return Fan Capacity (cfm)	Total SP (inches)	Return Fan Efficiency	Fan BHP	Motor Efficiency
HRU-1	4,700	3.5	65.0%	4.0	89.5%	6700	3.5	65%	5.7	91.0%

Table 5: Fan Parameters of the Dedicated Outside Air Handling Unit

Four decentralized HVAC systems serve conference rooms, the server room, and the telecom space. The following table summarizes the equipments' energy characteristics.

Decentralized Air Conditioning Units				
ID	Supply Airflow (cfm)	Total SP (inches)	Cooling EER	Heating COP
FCU-101	1550	1.5	12.75	4
FCU-102	800	1.5	12.75	4
WSHP-1-1	270	0.5	13.6	4
WSHP-B-1	950	1	13.6%	4

Table 6: Equipment Energy Characteristics for Decentralized HVAC Systems

Natural Ventilation Controls. The building is equipped with motorized window actuators that are controlled for night ventilation and natural ventilation during the day. The window switches will have a manual override via the DDC system to allow the windows to be opened or closed during appropriate environmental conditions.

Water Side. The building's heating and cooling source are 37 geothermal wells located below the structure. The geothermal system serves four water-to-water heat pumps that provide hot and cold water to the building's radiant floors and air handler.

Heat pumps. Three water-to-water heat pumps move energy from the geothermal condenser water loop to the building's change-over heating/cooling water system. In the heating season, the heat pumps provide the building with hot water and pull heat from the geothermal wells. In the cooling season, the heat pumps provide the building with chilled water and reject heat into the earth. A fourth water-to-water heat pump serves the building's heat recovery air handler.

Heat Pumps								
Unit ID	Capacity (tons)	EER	Heating Capacity (Btu/h)	COP	Load Side Water Flow (GPM)	Load Side Max WPD	Condenser Side Water Flow (GPM)	Condenser Side Max WPD
WWHP-1	10	14.3	170,000	2.77	34	17	34	15
WWHP-2	20	14.2	340,000	2.83	68	17	68	15
WWHP-3	20	14.2	340,000	2.83	68	17	68	15
WWHP-4	20	14.2	340,000	2.83	68	17	68	15

Table 7: Equipment Energy Characteristics for Heat Pumps

Pumps. 12 pumps are incorporated into the mechanical system. The ground loop pumps move condenser water through the geothermal wells. The Radiant Loop Pumps move water through the building's radiant systems. The heat pump pumps supply water to the heat pumps coils whenever the heat pump is operating. The following table summarizes the pumps energy parameters:

Pumps							
Unit ID	Service	Flow GPM	Head ft H2O	Pump Efficiency	Pump BHP	Motor Efficiency	Control
CWP-1	Ground Loop	210	85	65%	6.9	91.7%	VFD
CWP-2	Ground Loop	210	85	65%	6.9	91.7%	VFD
CH/HWP-1	Radiant Loop	200	70	65%	5.4	91.0%	VFD
CH/HWP-2	Radiant Loop	200	70	65%	5.4	91.0%	VFD
HPP-1	Heat Pump Source	84	20	65%	0.7	85.5%	Constant Speed
HPP-2	Heat Pump Load	84	20	65%	0.7	85.5%	Constant Speed
HPP-3	Heat Pump Source	84	20	65%	0.7	85.5%	Constant Speed
HPP-4	Heat Pump Load	84	20	65%	0.7	85.5%	Constant Speed
HPP-5	Heat Pump Source	84	20	65%	0.7	85.5%	Constant Speed
HPP-6	Heat Pump Load	84	20	65%	0.7	85.5%	Constant Speed
HPP-7	Heat Pump Source	84	20	65%	0.7	85.5%	Constant Speed
HPP-8	Heat Pump Load	84	20	65%	0.7	85.5%	Constant Speed

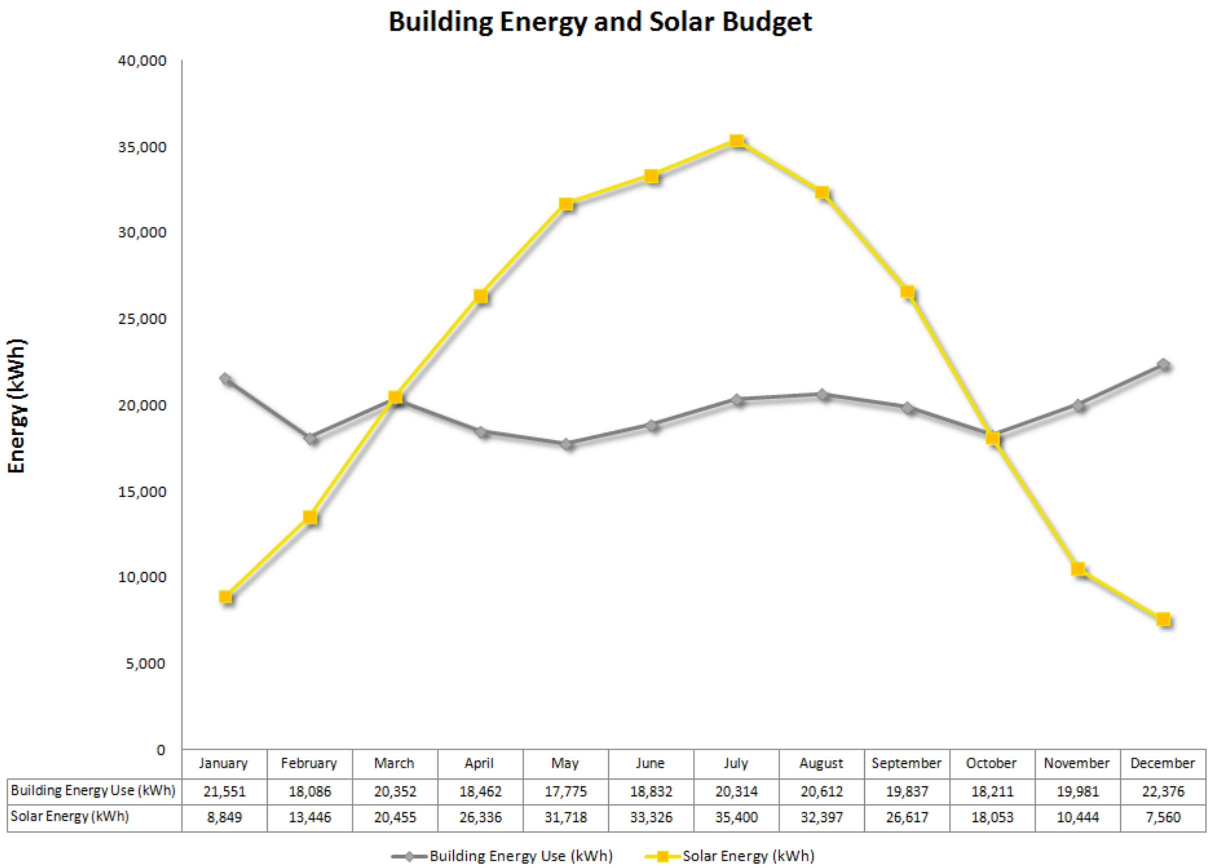
Table 8: Equipment Energy Characteristics for Pumps

Exhaust Fans. The building is equipped with three exhaust fans and one supply fan. The exhaust fans serve the parking garage exhaust, Seattle City Light transformer vault, and composter exhausts. A supply fan provides outside air and economizer ability to the building's decentralized air conditioning units.

MODELED PERFORMANCE

The building was predicted to use approximately 250,000 kWh/year in electrical energy; this is equivalent to an energy use index (EUI) of 16.7 kBTU/ft^2/yr. The PV system was sized to produce approximately 258,000 kWh. Figure 12 illustrates the predicted monthly energy consumption and solar generation. As can be seem from the Figure, the building is anticipated to product more energy than it consumes between March and October, and run an energy deficit for the balance of the year.

An overall breakdown of the building's projected energy use is illustrated in Figure 13.



	January	February	March	April	May	June	July	August	September	October	November	December
Building Energy Use (kWh)	21,551	18,086	20,352	18,462	17,775	18,832	20,314	20,612	19,837	18,211	19,981	22,376
Solar Energy (kWh)	8,849	13,446	20,455	26,336	31,718	33,326	35,400	32,397	26,617	18,053	10,444	7,560

Figure 12: Monthly Energy Consumption and Generation

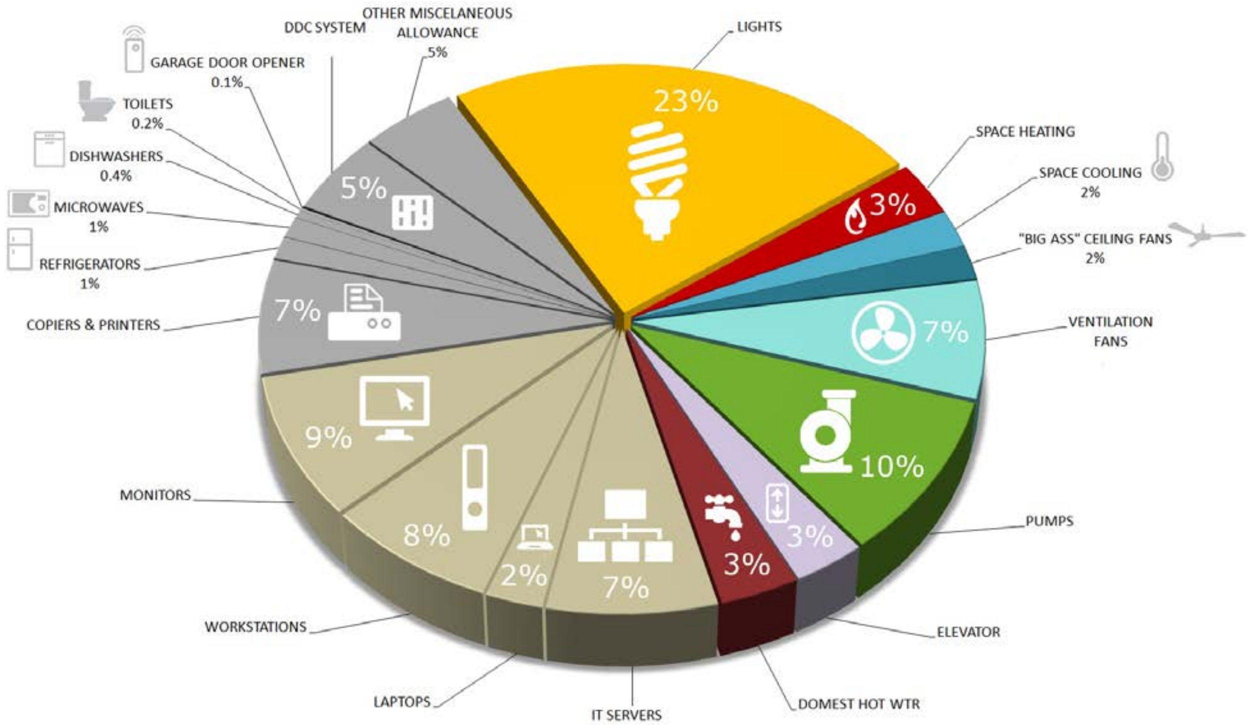


Figure 13: Projected Energy Use

ACTUAL ENERGY USE AND PRODUCTION

Actual building energy use for the past year is now available and the building appears to be outperforming the performance predictions. Based on the past 12 months energy performance, the Bullitt Center is operating at an EUI of about 9.4 kBTU/ft^2/yr. This is a 44% improvement over the predicted EUI of 16.7 kBTU/ft^2/yr.

Actual energy production over the past 12 months has been 239,783 kWh. This is 7% less than the predicted production of 257,770 kWh.

Overall the Bullitt Center has generated a surplus of 99,333 kWh over the past 12 months operation.

Figure 14 illustrates the predicted energy use of production and actual energy use and production.

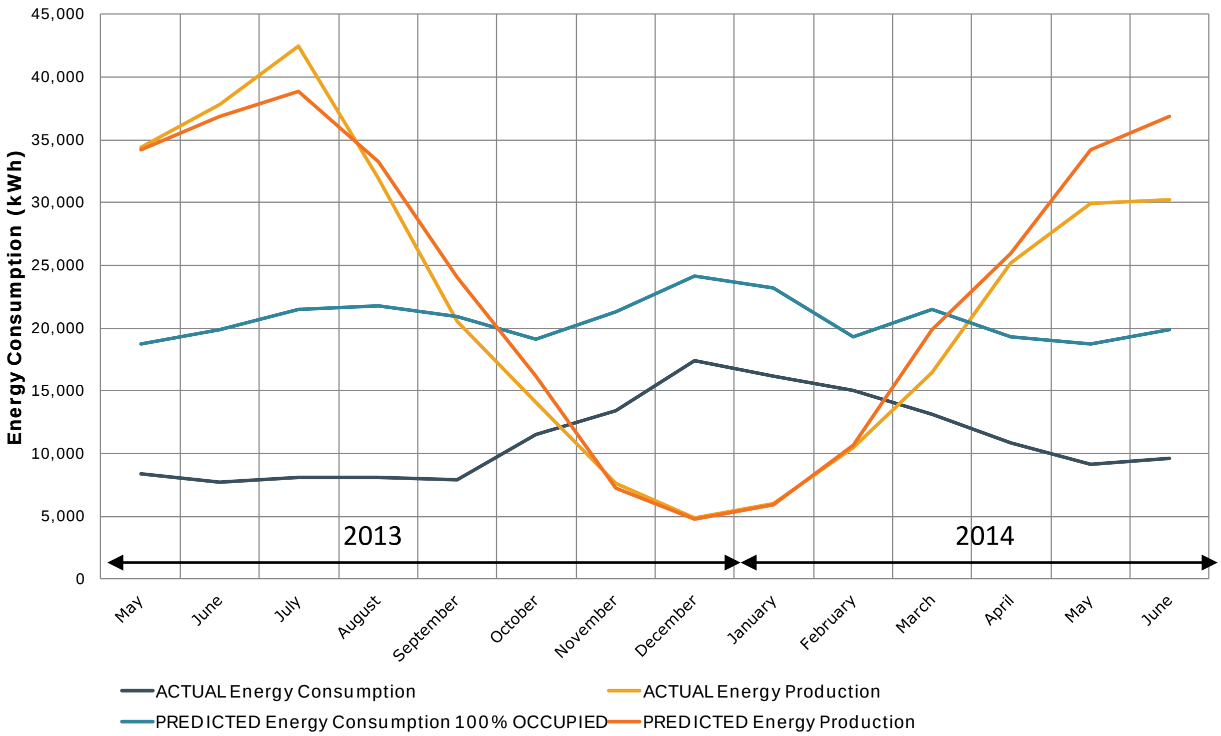


Figure 14: Actual and Predicted Energy Performance with Full Occupancy

ACTUAL OCCUPANCY

The building was built as a speculative office building and as such was not fully occupied from the start of the analysis period. As is seen in Figure 13, much of the building's total energy use is driven by internal occupancy: 19% of the building's predicted energy use is tied to occupant computers, 3% to elevator use, and 3% to domestic hot water use, all of which varies in direct proportion to building occupancy. 14% of predicted energy use is tied to server and printer energy and 23% is tied to lighting, both of which correlate to occupancy, though less strongly than computer use. The total energy use correlating to occupancy is more 62%.

The building is currently occupied on 5 of the 6 leasable floors. Table 9 summarizes the current tenants and their dates of occupancy:

Floor	Occupant	Date Occupied
Basement	NA (mechanical space)	NA
1	International Living Future Institute	March 2013
2	Hammer & Hand and University of Washington Integrated Design Lab	Jan 2014 and March 2013
3	Unoccupied	NA
4	Co-work Space	March 2013
5	Intentional Futures	March 2013
6	PAE & Bullitt Foundation	April 2013, March 2013

Table 9: Summarizes the Building's Occupancy History

The exact occupant density of each of the floors is unknown, but anecdotal data suggests that it is less than the 150 ft^2/person density assumed in the modeling. 150 ft^2/person corresponds to about 35 people/floor.

In order to understand the effect of a reduced occupancy on the building's predicted performance, the energy model was modified to reflect 75%, 50%, and 25% occupancy levels. Schedules for occupancy, plug-load equipment (computers, etc.), lighting, and demand-controlled ventilation were adjusted to simulate the reduced occupancy level.

Results show that the building's energy use best corresponds to the modeled 25% occupied data. The results are illustrated in Figure 15.

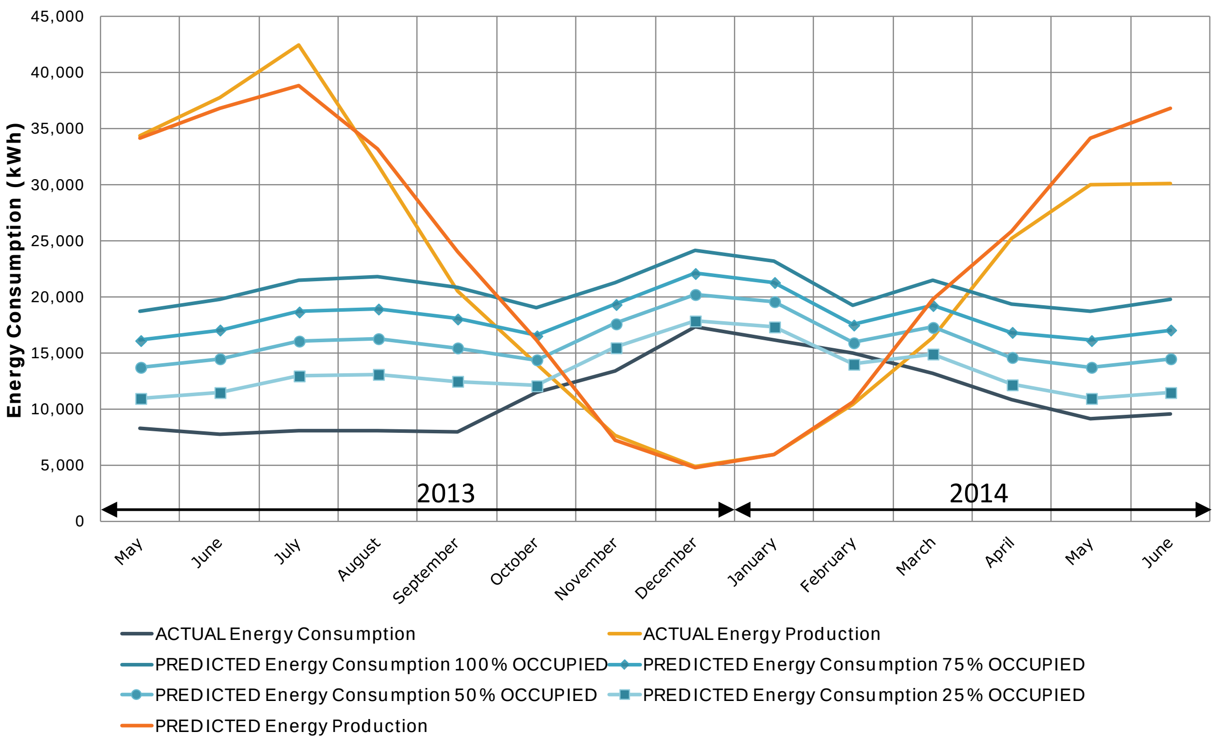


Figure 15: Actual and Predicted Energy Performance with Lower Occupancy

ACTUAL WEATHER

The Bullitt Center is equipped with a roof-mounted weather station. Temperature and humidity data for the period of analysis were retrieved for comparison to the modeled data. Figure 16 illustrates the data obtained from the TMY3 file used in the analysis (Seattle Boeing Field TMY3). Figure 17 illustrates the actual temperature and humidity over the past 12 months at the Bullitt Center. Figure 18 illustrates the difference between the two weather data sets.

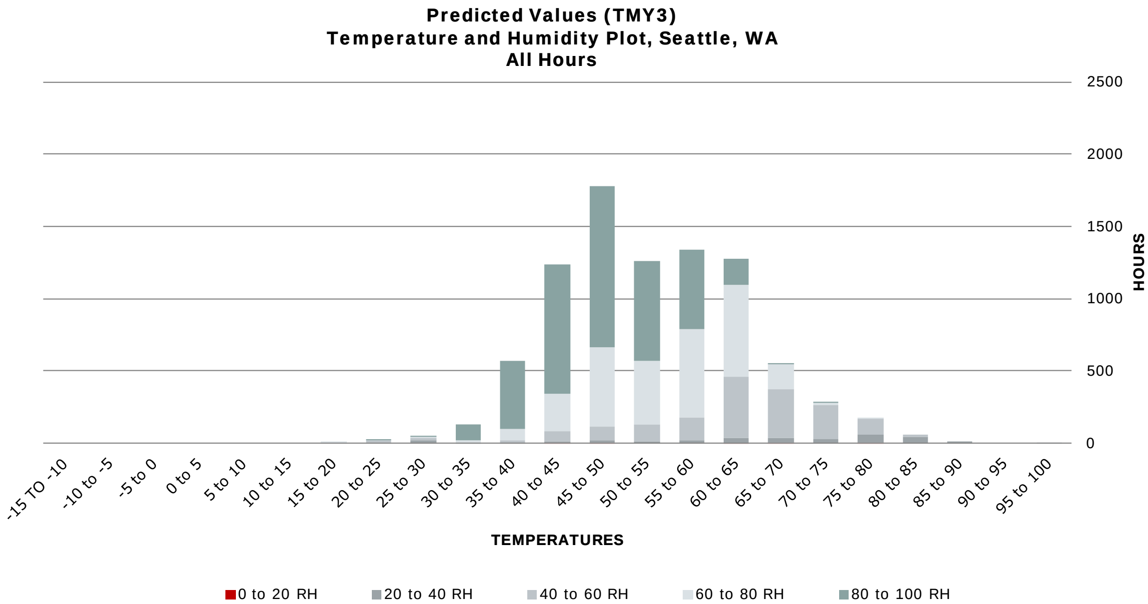


Figure 16: Predicted Weather Data

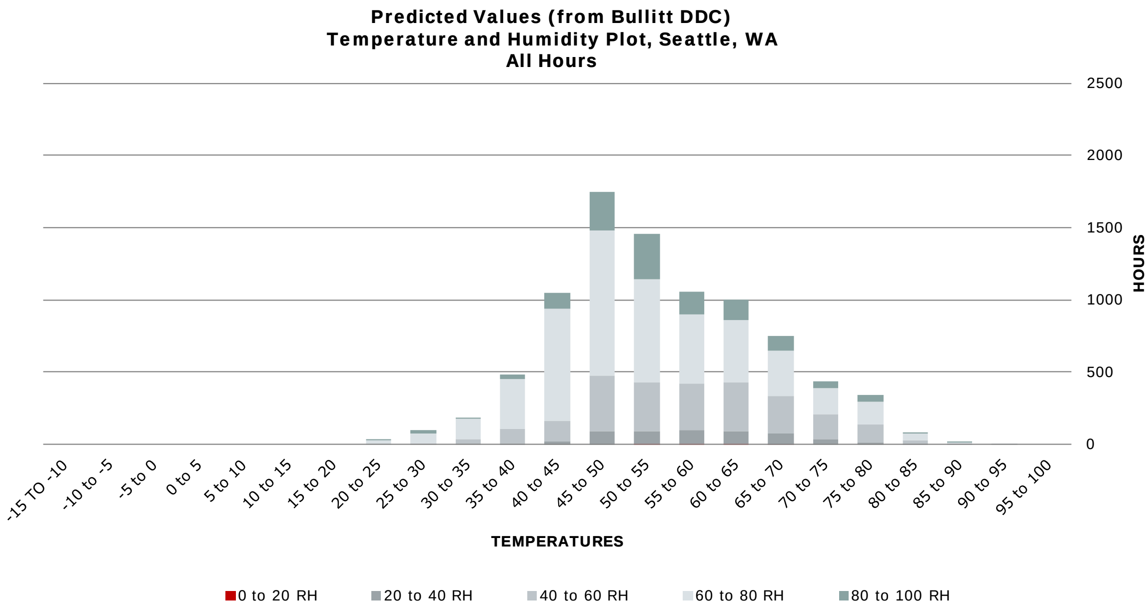


Figure 17: Actual Weather Data

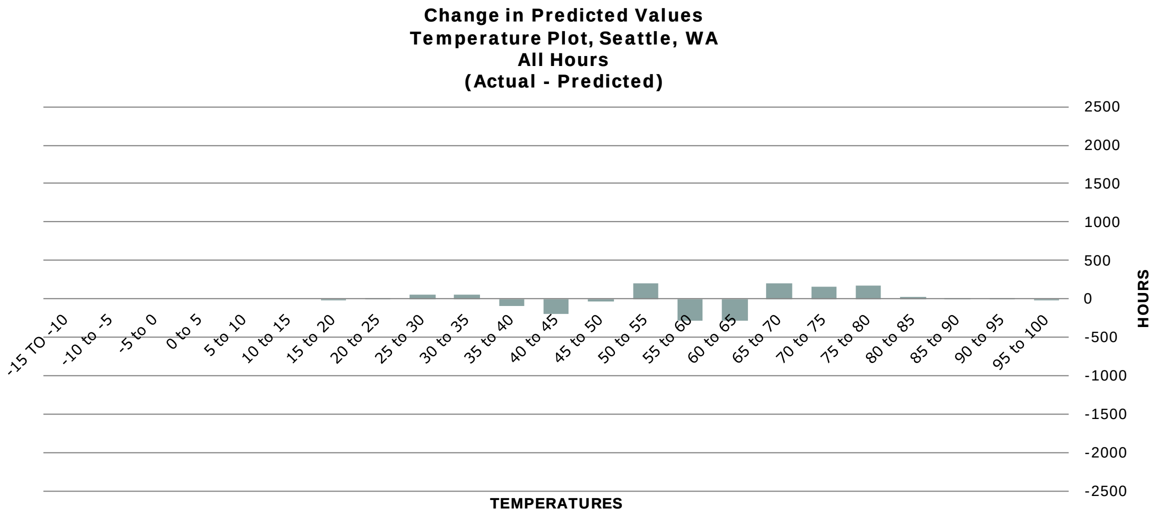


Figure 18: Difference in TMY3 and Actual Temperature Values

The weather data shows fairly close correlation to the assumed weather data, with the exception of relative humidity. The assumed weather file has significantly higher humidity between 35 and 65F. While this is a substantial difference, because of the ambient air's low moisture capacity at low temperatures, it is not likely that higher humidity at these temperatures would have resulted in significant dehumidification energy. The model showed only about 5% of the total predicted cooling energy is associated with latent cooling. Since cooling represents only 2% of the building's total energy use, the latent cooling portion is about 0.1% of the total building energy. It is concluded that the variation on relative humidity is not a factor in the building's lower energy use.

THERMAL COMFORT

The Bullitt Center is equipped with a hydronic radiant floor heating and cooling system. Generally, the system is sized for heating and has the ability to operate in cooling mode when needed, though is not specifically sized for cooling. The building's DDC system allows trending of temperature data from the building's air and slab temperature sensors. Ventilation air is conditioned to room air temperature, but is not designed as part of the building's heating and cooling system.

To gain an understanding of the building's heating and cooling characteristics, the following data was retrieved from the DDC system:

1) 6th Floor North and South Peak Summer
2) 6th Floor North and South Mid Autumn
3) 6th Floor North and South Peak Winter

The data provide a snapshot of the building's thermal performance.

Summer Performance. Weather data for August 5 through August 11, 2013 were reviewed for summer performance. This period represented the year's hottest heat wave, during which ambient temperatures reached 86F at the Bullitt Center. Maximum space temperature reached 80F, and the maximum slab temperature was recorded at 77F. This resulted in a predicted mean vote (PMV) of -0.1 [1] [2]. A PMV between -0.5 and 0.5 is considered comfortable, with values below zero being cold and above zero warm. Therefore, even at 80F, air temperature the space calculates as slightly cool because of the slab temperature, and air movement. Despite the cool PMV calculation, a lower overall air temperature would be more desirable, since the PMV can be increased by reducing the internal fan speed, thereby giving the system greater capacity for an even warmer day.

Operable windows actuated to provide night flush, but do not appear to be optimized. It is apparent from the data that space air temperature equalizes very quickly to the slab temperature when the automatic windows are closed. For example, on August 8 at 3 am, the windows start to close, with space air temperature at about 69F, ambient air temperature at about 62F, and slab temperature at about 75F. The slab temperature is declining and the overall space comfort would benefit from an additional decrease in slab temperature associated with the free night-cooling. However, the windows close at 3:00 AM and the space temperature has equalized to the slab temperature within about 30 minutes. Figure 19 illustrates this.

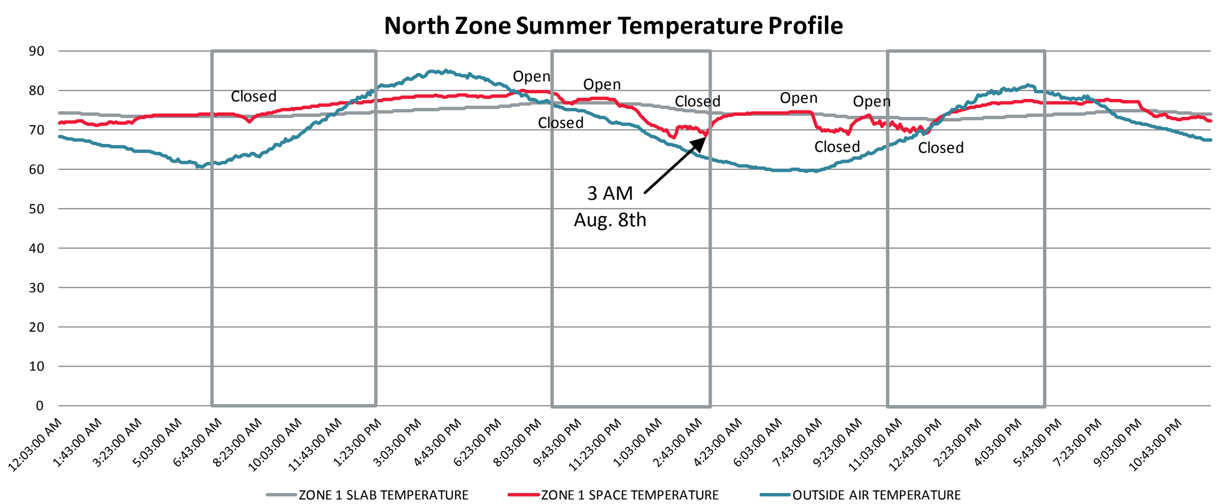
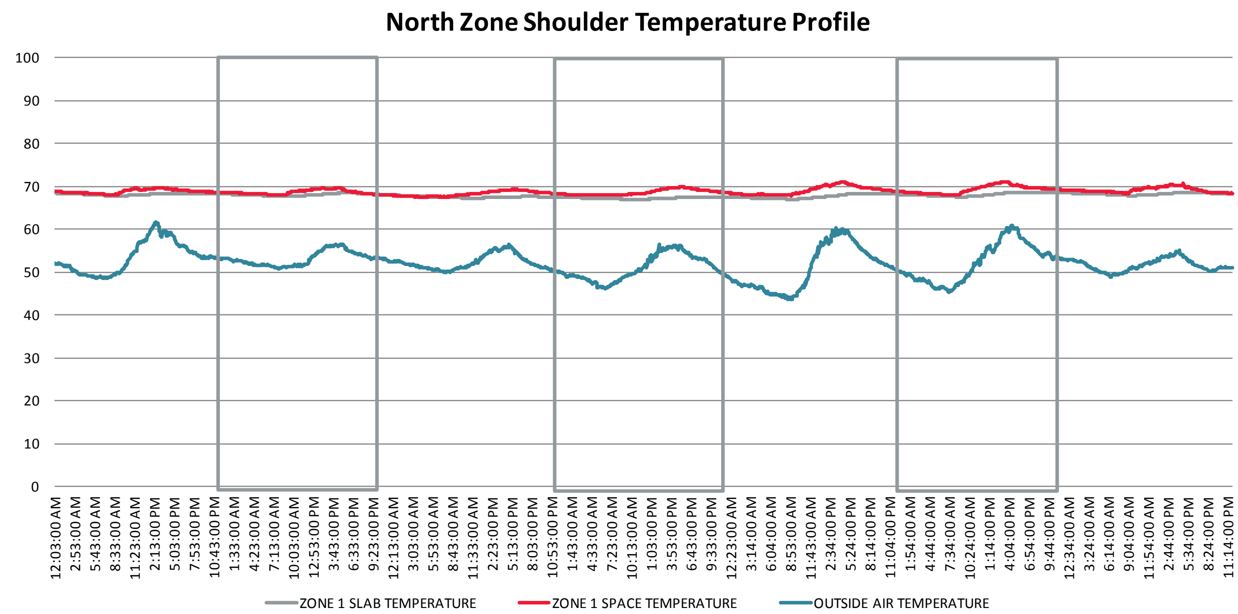


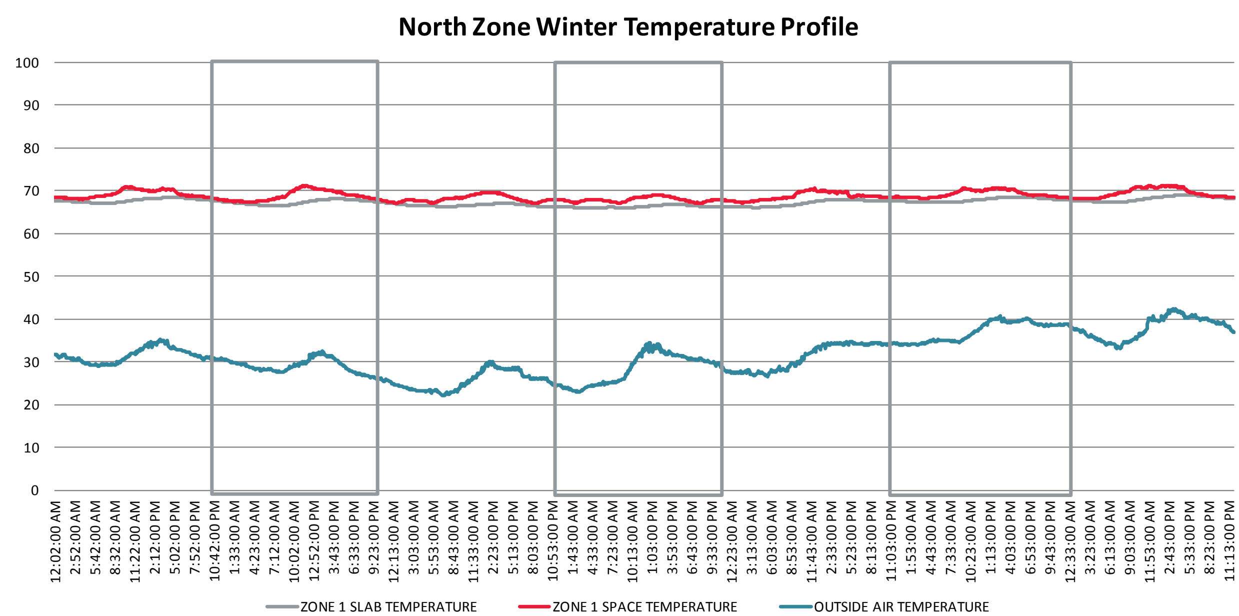
Figure 19: August 7th and 8th Temperature Data

An improvement to this routine would be to allow the space to continue to night cool until the slab temperature hits the daytime heating limit plus an adjustable offset, or if the time is within one hour of occupancy and the space air temperature is below setpoint. This improvement would improve the performance of the night flush and provide a more comfortable summer condition.

Shoulder Season Performance. Weather data for October 10 through October 16, 2013 were reviewed for shoulder season performance. This period represented typical shoulder season operation. Outside air temperatures ranged from 44 to 62 ^{o}F, typical of Seattle during this time of year. The indoor space temperatures were very steady. Notable is that the slab temperature exceeded the space air temperature for only about 6 hours of the entire week (during the night of October 11-12). Since the slab is the heating/cooling source for the space, this indicates that the zone (a north-facing perimeter zone) was in cooling more for nearly the entire time.



Winter Season Performance. Weather data for December 5 through December 11 2013 were reviewed for winter performance. This period represented one of the coldest weeks of the year in Seattle, during which temperatures ranged between 22 and 42 F. Interior temperatures ranges from 67F to 71, with slab temperatures between 66 and 69F. There are no hours during this period when the slab temperature exceeded the space temperature. This indicates that the envelope was sealing very well and the space had not yet reached its balance point temperature.



CONCLUSIONS

Energy Performance. The building is exceeding its energy performance goals by about 44%. Modeled data suggests that while a lower occupancy rate has a signiciant influence of the building's energy use, the modeled data only correlates well at a 25% occupancy level. Five of the building's six floors are currently occupied, and while the density of occupancy may be less than the assumed density, it is likely that the building's systems are performing better than initially predicted.

Thermal Performance. Energy performance correlates well to the comfort data which shows that the building is very rarely in a heating mode. Much of the building's cooling can be achieved with natural ventilation and night flush, resulting in very low HVAC system operation. Occupant satisfaction with the space is high, though some "cold complaints" have resulted in setpoint adjustments to increase the frequency of heating.

REFERENCES

[1] Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Moon Dustin, and Steinfeld Kyle, 2013, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

[2] ASHRAE, *ASHRAE/ANSI Standard 55-2010 Thermal environmental conditions for human occupancy.* 2010, American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA.