A Study of the Energy Impacts of Residential Skylights in Different Climates

Prepared for

VELUX®

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Prepared by

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1 Executive Summary

This analysis was conducted to determine the energy cost impacts of achieving good minimum daylight levels in a one-story, open plan single-family "home" through varied fenestration. Using DOE-2 energy modeling software, the analysis considers only the heating and cooling cost impacts of different variations of area and location of openings filled by similarly constructed glazed fenestration.

To make this study particularly relevant to today's design and construction standards, the test home was modeled under code-compliant conditions of California's Title 24 regulations (California Energy Commission, 2008), Residential Package D. The test home was also considered in two different California climates: Climate Zone 2, which is a moderate climate in the Napa Valley and is heating dominated, and Climate Zone 9, which is in the Los Angeles area and is cooling dominated. These locations do not represent the most extreme climates in California; rather, they were selected for their differing climates as well as for their relevance to California, as they are some of the more populous regions.

The comparison was expanded into seven more major cities of varying climate types across the United States. Each home was modeled using local building codes, energy codes, and utility rate structures. The additional cities include Boston, Chicago, Denver, Dallas, Minneapolis, Orlando, and Seattle.

The baseline modeled home has a maximum 20% window to floor area (with no skylights), which represents the prescriptive limit allowed by California Building Code, with windows evenly distributed on all facades. This baseline was found to achieve an average daylight factor of 5%. The window area was varied, reduced to as low as 8% window to floor area (minimum allowed by local building codes), and grouped in two different ways: either equally distributed on all facades, or distributed with 70% of the window area on the north and south facades. Skylight area was added as necessary on the sloped roof to maintain the baseline average daylight factor of 5% under a CIE overcast sky. Skylights were distributed three ways: north-facing, south-facing, or with equal distribution.

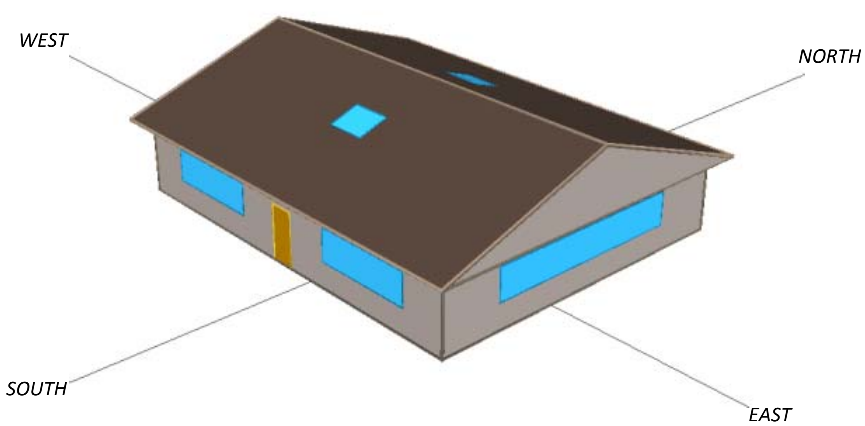


Figure 1: Modeled Home

This methodology, which used combinations of three window to floor areas (20%, 14%, and 8%), two window distributions (equal on all facades, or 70% north/south and 30% east/west), three skylight orientations (all north, all south, or equal distribution north and south), and nine different cities, generated a total of 126 model runs.

1.1 Key Results

Introducing skylights allows the total fenestration area (windows plus skylights) to be reduced from a maximum 20% of floor area to as low as 12% of floor area while achieving the same baseline average daylight factor target of 5%, and reduces annual heating and cooling energy use and costs in all but two of the 108 models with skylights analyzed.

In other words, when different combinations of skylights and windows are used to achieve the same target daylight factor, the heating and cooling energy cost savings are almost always greater when equivalent daylight comes from top-lighting (skylights) rather than side-lighting (windows). The greatest savings for each city differ depending on skylight orientation, window distribution, climate type, and utility rate structure.

See results summarized in the following tables.

Table 1: Annual Cost Savings Relative to Base*. Highest savings in dark green, second highest savings in light green, negative savings in red text.

Model	ASHRAE 90.1 Climate Zone: / Climate type:	ORLANDO 2A Hot-Humid	DALLAS ** 3A Warm-Humid	LOS ANGELES (CA-CZ9) 3B Warm-Dry	NAPA (CA-CZ2) 3C Warm-Marine	SEATTLE 4C Mixed-Marine	BOSTON 5 Cool	CHICACO ** 5A Cool-Humid	DENVER 5B Cool-Dry	MINNEAPOLIS 6A Cold-Humid
1 (base)	Windows: Maximum, equally distributed Skylights: None	-	-	-	-	-	-	-	-	-
2	Windows: Maximum, 70% on north/south Skylights: None	$4	$8	$14	$30	$7	$6	$5	$12	$6
3	Windows: Average, equally distributed Skylights: Minimum, north roof only	$4	$3	$12	$17	$8	$3	$4	-	$4
4	Windows: Average, 70% on north/south Skylights: Minimum, north roof only	$6	$9	$23	$40	$12	$6	$7	$7	$8
5	Windows: Minimum, equally distributed Skylights: Maximum, north roof only	$7	$4	$22	$31	$17	$4	$7	-$2	$8
6	Windows: Minimum, 70% on north/south Skylights: Maximum, north roof only	$9	$8	$28	$44	$19	$7	$8	$3	$11
7	Windows: Average, equally distributed Skylights: Minimum, south roof only	$1	$5	$2	$8	$12	$8	$4	$6	$9
8	Windows: Average, 70% on north/south Skylights: Minimum, south roof only	$4	$10	$11	$30	$16	$12	$6	$14	$16
9	Windows: Minimum, equally distributed Skylights: Maximum, south roof only	$2	$7	$2	$16	$25	$15	$6	$11	$26
10	Windows: Minimum, 70% on north/south Skylights: Maximum, south roof only	$4	$9	$8	$29	$27	$18	$8	$16	$29
11	Windows: Average, equally distributed Skylights: Minimum, equal north/south	$2	$3	$7	$13	$10	$4	$4	$2	$6
12	Windows: Average, 70% on north/south Skylights: Minimum, equal north/south	$5	$8	$17	$35	$14	$9	$6	$10	$13
13	Windows: Minimum, equally distributed Skylights: Maximum, equal north/south	$5	$8	$13	$24	$20	$9	$7	$4	$13
14	Windows: Minimum, 70% on north/south Skylights: Maximum, equal north/south	$6	$9	$20	$37	$22	$12	$9	$9	$18

**The runs in Dallas and Chicago with the greatest savings differentiated by less than $1. As such no optimum run has been highlighted.

Table 2: Annual Percentage of HVAC Cost Savings Relative to Base*. Highest savings in dark green, second highest savings in light green, negative savings in red text.

Model	ASHRAE 90.1 Climate Zone: / Climate type:	ORLANDO 2A Hot-Humid	DALLAS** 3A Warm-Humid	LOS ANGELES (CA-CZ9) 3B Warm-Dry	NAPA (CA-CZ2) 3C Warm-Marine	SEATTLE 4C Mixed-Marine	BOSTON 5 Cool	CHICACO ** 5A Cool-Humid	DENVER 5B Cool-Dry	MINNEAPOLIS 6A Cold-Humid
1 (base)	Windows: Maximum, equally distributed Skylights: None	-	-	-	-	-	-	-	-	-
2	Windows: Maximum, 70% on north/south Skylights: None	1.4%	2.1%	5.1%	4.5%	1.2%	1.0%	1.1%	1.7%	0.8%
3	Windows: Average, equally distributed Skylights: Minimum, north roof only	0.5%	0.9%	3.3%	2.4%	1.8%	0.7%	0.8%	-0.8%	0.6%
4	Windows: Average, 70% on north/south Skylights: Minimum, north roof only	2.2%	2.3%	7.1%	6.1%	2.2%	0.9%	1.5%	0.8%	1.1%
5	Windows: Minimum, equally distributed Skylights: Maximum, north roof only	2.2%	1.0%	6.4%	4.4%	3.6%	1.0%	1.9%	-1.1%	1.3%
6	Windows: Minimum, 70% on north/south Skylights: Maximum, north roof only	3.1%	1.9%	8.4%	6.7%	3.8%	1.4%	2.2%	0.2%	1.7%
7	Windows: Average, equally distributed Skylights: Minimum, south roof only	0.2%	1.3%	1.2%	1.8%	3.1%	1.5%	1.0%	1.1%	1.4%
8	Windows: Average, 70% on north/south Skylights: Minimum, south roof only	1.4%	2.5%	4.2%	5.8%	3.4%	2.9%	1.7%	3.1%	2.5%
9	Windows: Minimum, equally distributed Skylights: Maximum, south roof only	0.8%	1.7%	1.5%	3.2%	5.6%	3.4%	2.0%	2.8%	3.9%
10	Windows: Minimum, 70% on north/south Skylights: Maximum, south roof only	1.8%	2.3%	2.7%	5.8%	6.6%	4.3%	2.2%	4.1%	4.3%
11	Windows: Average, equally distributed Skylights: Minimum, equal north/south	0.5%	0.9%	2.2%	1.9%	1.0%	1.1%	0.5%	0.3%	0.9%
12	Windows: Average, 70% on north/south Skylights: Minimum, equal north/south	2.2%	2.0%	5.4%	5.6%	2.9%	2.3%	1.6%	1.2%	1.9%
13	Windows: Minimum, equally distributed Skylights: Maximum, equal north/south	0.8%	1.9%	4.0%	4.2%	4.9%	2.4%	1.9%	1.3%	1.9%
14	Windows: Minimum, 70% on north/south Skylights: Maximum, equal north/south	2.2%	2.2%	6.0%	6.5%	5.0%	2.3%	2.3%	1.7%	2.7%

*Percentage of HVAC savings excludes energy costs of interior/exterior lighting, equipment/plug loads, and domestic hot water, which are consistent between each city's different models.
**The runs in Dallas and Chicago with the greatest savings differentiated by less than $1. As such no optimum run has been highlighted.

Table 3: Annual kBtu Savings by City. Maximum savings highlighted in dark green, second highest in light green, and kBtu increases shown in red text.

Model:		ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
	ASHRAE 90.1 Climate Zone:	2A	3A	3B	3C	4C	5	5A	5B	6A
	Climate type:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	Windows: Maximum, equally distributed Skylights: None	-	-	-	-	-	-	-	-	-
2	Windows: Maximum, 70% on north/south Skylights: None	250	435	363	483	264	374	284	566	494
3	Windows: Average, equally distributed Skylights: Minimum, north roof only	139	-288	-13	-6	533	2	416	-681	343
4	Windows: Average, 70% on north/south Skylights: Minimum, north roof only	248	79	278	306	749	325	646	-193	680
5	Windows: Minimum, equally distributed Skylights: Maximum, north roof only	188	-587	-144	-225	1,063	105	1,029	-1,371	683
6	Windows: Minimum, 70% on north/south Skylights: Maximum, north roof only	256	-388	72	2	1,228	276	1,104	-1,059	865
7	Windows: Average, equally distributed Skylights: Minimum, south roof only	127	165	203	717	1,031	1,024	1,234	790	1,355
8	Windows: Average, 70% on north/south Skylights: Minimum, south roof only	240	532	488	1,018	1,247	1,250	1,467	1,281	1,694
9	Windows: Minimum, equally distributed Skylights: Maximum, south roof only	158	423	383	1,514	2,251	2,144	2,561	1,769	2,809
10	Windows: Minimum, 70% on north/south Skylights: Maximum, south roof only	219	622	592	1,733	2,419	2,316	2,640	2,082	3,088
11	Windows: Average, equally distributed Skylights: Minimum, equal north/south	47	-60	57	316	685	468	778	-42	702
12	Windows: Average, 70% on north/south Skylights: Minimum, equal north/south	252	210	345	621	901	691	1,012	452	1,039
13	Windows: Minimum, equally distributed Skylights: Maximum, equal north/south	183	-120	193	608	1,560	1,030	1,650	109	1,701
14	Windows: Minimum, 70% on north/south Skylights: Maximum, equal north/south	251	79	303	831	1,729	1,201	1,829	418	1,880

1.2 Observations

- As seen in the tables above, the runs with the highest and lowest kBtu savings do not necessarily directly correlate with the runs having the highest and lowest energy cost savings. The utility rate structure has a great impact as to which daylight delivery system saves the most money in each city. Projects considering using skylights as a daylight delivery system in lieu of windows should check their utility rate structure to see how this could impact the choice of skylight orientation. Refer to Appendix A for utility rate information used in this analysis, and Appendix E for an energy use breakdown.
- The results in Dallas and Chicago have the highest savings in multiple runs that differentiate by less than $1. While all runs show savings relative to the base, no optimum run has been determined for these cities.
- Cities with humid climates that are hot, warm, or cool (Orlando, Dallas, Chicago) have the lowest cost savings potential from a skylight daylight strategy, only 2-3% HVAC cost savings. There is very little differentiation between savings from using different skylight and window orientations. The savings are so small that there is not an obvious optimal orientation as in other cities. However Minnesota, which is humid but cold, is the exception to this, and this model shows distinct benefits from the solar heat gain from south skylights.
- In cold, cool, dry, or mixed climates (Boston, Denver, Seattle, Minneapolis), the highest cost savings can be achieved by using south facing skylights for daylight delivery, thus optimizing the solar heat gain. These same cities had both the highest and second highest energy cost savings with maximum southern skylights for both window orientations. The runs in these cities that had the highest energy cost savings also have the highest kBtu savings; however, this correlation does not exist in any of the other cities.
- The colder the climate, the higher the annual kBtu savings. This is due to the high kBtu value of natural gas, and a result of the positive solar heat gain. Model runs with kBtu increases occur primarily when the southern exposure is reduced. Minnesota has the highest potential annual kBtu savings of all the cities, seen in the runs with maximum southern skylights.
- In almost all of the warm or hot climates (Napa, Los Angeles, Orlando), the greatest energy cost savings come from minimizing the glazing and solar heat gain. These cities saved the most money from using north facing skylights for daylight delivery. The exception to this is Dallas, which has enough heating load to offset the cooling savings.
- The cities with the highest potential percentages of HVAC energy cost savings (Napa and Los Angeles) also have the highest electricity costs. The potential savings are primarily from a reduced cooling load generated by using north-facing skylights and minimized total glazing area.
- The two models that did not achieve HVAC cost savings with skylights were the two models in Denver that implemented all skylights on the north facing roof, with none on the south, and windows evenly distributed on all facades. Denver has a climate that benefits greatly from passive solar design, and these two models were penalized by the lower amount of southern exposure and minimized winter solar heat gain, resulting in slight energy cost increases. This

city has its highest savings when maximizing the south-facing skylights and minimizing west facing glazing.

- In all runs, not surprisingly, the runs that have more windows on the north and south facades performed better than every paired run with windows distributed equally on all facades.

1.3 Other Analysis Results

A Time Dependent Valuation (TDV) economic analysis was performed on the California cities. Under TDV, the value of electricity differs depending on time of use (hourly, daily, and seasonal) and the value of natural gas differs depending on season. A TDV analysis is used as the foundation of Title 24 measure analysis, and gives a bigger picture of the cost of energy over the life cycle of a building.

When analyzed with a 30-year lifecycle, all parametric runs showed TDV savings relative to the baseline model. However the TDV analysis methodology puts a higher life cycle cost to gas usage than is reflected by current utility rates(Energy & Environmental Economics, 2011), and as such the models with the highest TDV savings were not the same as those with the highest energy cost savings. In Napa, California climate zone 2, the model with the greatest TDV savings was found in model #10, which had a 70/30 window distribution and 100 square feet of skylights on the south roof. This model provided the greatest solar gain benefit and heating energy savings, while still offering cooling savings. In Los Angeles, climate zone 9, the model with the greatest TDV savings was found in model #14, which had the same 70/30 split of windows, but instead had skylights split evenly between north and south.

The fact that total fenestration area is being reduced in the parametric model runs leads to the question of whether the quality or quantity of the daylight is being compromised in the name of energy savings, which could potentially lead to higher lighting energy use. To answer this, two climate-based metrics were considered: daylight autonomy (DA) and useful daylight illuminance (UDI). While these metrics are not true measures of daylight quality, they are indicative of how useful the daylight can be in a residential setting, and offer a comparison of yearly daylight characteristics between the baseline and all test models.

While the daylighting analysis was limited in scope in that only three models were analyzed for each of the two California cities, it was found that the model with the highest percentage of daylit hours in each city was the baseline model, which has the maximum vertical windows distributed equally around the house and no skylights. However the model that had the highest percentage of hours in the most useful daylight range (between 10-200 FC, or 100-2000 lux) was also the model that achieved the highest energy cost savings in both California cities, with a 70/30 window split and north facing skylights, which allows more glare-free daylight coming in.

The relevance lies in the fact that better quality daylight has the potential to influence occupant behavior in a positive way. Visual activities in a home are quite varied and require different light levels – activities vary between watching television, cooking, reading, home office work, etc. – but good daylight is still important. For example, a resident chopping vegetables under glare-free daylight is less likely to close blinds to block glare, which leads to a better chance that electric lights might be left off during the day.

Please see details of this analysis in the following report.

1.4 Recommendations for Future Study

The results of this analysis suggest that further study of this topic and broadening the scope will be vital as regulatory agencies consider how to regulate the energy impacts of adding skylights in residential buildings.

Currently, most energy codes consider skylights to only increase a home's energy use, rather than as an efficiency measure. Changing this approach could have significant implications on the development of codes, standards, and incentive-based building programs. The following are suggestions of additional parameters, baselines, or metrics for future study of this subject.

1. **Setting a code baseline.** In most performance-based code compliance paths (both residential and commercial), the baseline building must use the same skylight type, areas, and locations as the proposed building, up to a prescribed percentage. Should residential and/or commercial energy codes have an option to implement minimum/maximum prescriptive daylight levels instead, in order to represent energy savings from adding skylights and reducing vertical windows? This would be difficult to implement and enforce in a residential setting, particularly in a prescriptive path, but further studies could consider implementing the calculation methodology in this report to determine different compliance paths.

2. **Different home types.** This simplified house model had no space divisions. How would the results change if it was implemented partitioned spaces or multiple stories? If the skylights also faced east/west instead of just north/south?

3. **Different surroundings.** This analysis ignored the potential effect of external components, such as nearby homes, buildings, and landscaping. How do the results change in a more suburban or urban environment?

4. **Different daylight delivery devices.** Evaluate the use of tubular daylighting devices, plastic skylights, and windows of varying heights and locations (such as clerestory windows) in a similar application.

5. **Different daylight target methodology.** How would the results change if the glazing areas were derived based on uniform daylight autonomy or useful daylight index rather than daylight factor?

6. **Further daylight analysis.** In order to ensure that daylight quality was not being sacrificed in the name of energy savings, this analysis considered daylight autonomy and useful daylight

illuminance. This analysis was performed for only three of the fourteen model cases, which were selected as the most relevant, but further analysis could consider the daylight quality of the other cases as well. How do other cases compare? How do the results of DA and UDI change if blinds are not used to block direct sunlight?

2 Methodology

2.1 Model Parameters

The baseline one-story single family home under consideration is 2000 square feet – 50 feet in the east-west direction, by 40 feet in the north-south direction, with the roofline running east-west. The test home has 9' high walls and a 4:12 roof pitch with a 2' roof overhang. The home is heated with a gas-fired furnace and cooled with an air conditioner. System efficiencies meet local code baselines for each city. Please see more details of the building systems in Appendix A and B.

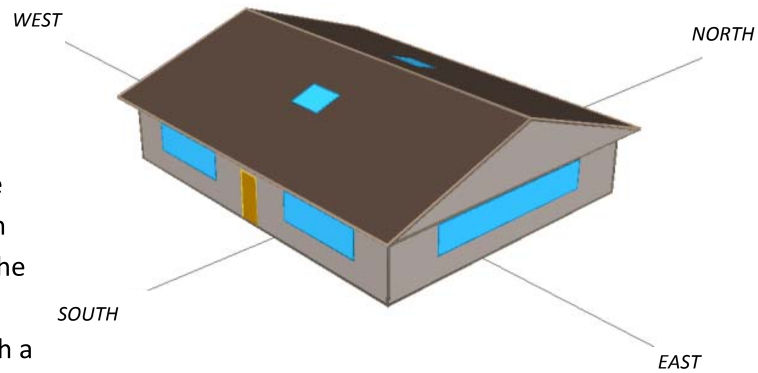


Figure 2: Single family test home

There are windows of varying area on all four sides along with a front door and back door. Skylights of varying area are considered on the north roof, south roof, or both. Windows were considered to be either equally distributed on all four sides, or weighted more heavily on the north and south walls (70% north/south, 30% east/west).

These combinations of parameters along with the methodology outlined in the following sections results in the creation of (14) different test runs for each city as follows:

Table 4: Model Parameters

Model Number	*Skylight Orientation*	*Window Area*	*Vertical Window Distribution*
1 (Baseline)	None	Maximum (20% window to floor area)	50% N/S, 50% E/W
2			70% N/S, 30% E/W
3	North only	Average (14% window to floor area)	50% N/S, 50% E/W
4			70% N/S, 30% E/W
5		Minimum (8% window to floor area)	50% N/S, 50% E/W
6			70% N/S, 30% E/W
7	South only	Average (14% window to floor area)	50% N/S, 50% E/W
8			70% N/S, 30% E/W
9		Minimum (8% window to floor area)	50% N/S, 50% E/W
10			70% N/S, 30% E/W
11	50% North, 50% South	Average (14% window to floor area)	50% N/S, 50% E/W
12			70% N/S, 30% E/W
13		Minimum (8% window to floor area)	50% N/S, 50% E/W
14			70% N/S, 30% E/W

The window area parameters (maximum, minimum, and average) were selected based on the maximum and minimum allowable glazing areas given by California codes as outlined in the following sections.

The baseline home is then modeled in nine different climates, for a total of 126 model runs. See “Site Selection” and Appendix B for more details on each climate.

2.2 Codes and Standards

The methodology of this analysis is firmly rooted in a code-baseline building that could be built today in California, under the provisions of the California Building Standards Code in Title 24 (2010 edition) of the California Code of Regulations, following requirements for the design and construction of a building's structural, plumbing, electrical and mechanical systems, fire and life safety, energy conservation, green standards, and accessibility. Refer to Appendix A for more details of the building systems.

2.3 Site Selection

In order to illustrate the fenestration effects in different climates, two different sites were originally selected for the analysis: California’s climate zone 2 (Napa Valley) and climate zone 9 (Los Angeles). Both climates are relatively mild with high population densities, though Zone 2 is a more heating-dominated climate than Zone 9.

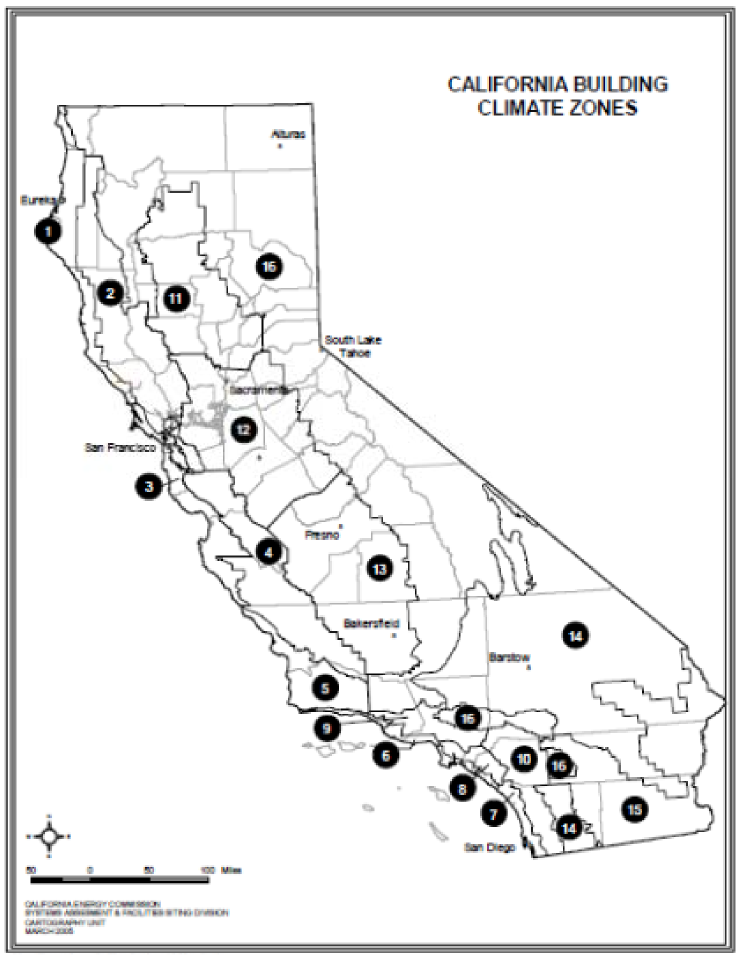


Figure 3: Climate Zones (California Energy Commission, 2008)

California Climate Zone 2

This zone includes the hilly Coastal range to the edge of the Northern Central Valley and has a coastal climate, influenced by the ocean approximately 85% of the time and by inland air 15% of the time. HDD dominates the climate design, although some cooling is necessary in the summer. There are many microclimates in this varied geography that are affected by proximity to the ocean and elevation. Marine air influence lessens with distance from the San Francisco Bay Area. Cold air flows downhill to the valley floors, canyons, and land-troughs. Winters are cool and mild, slightly warmer in comparison to Zone 1. The summers are very comfortable and often windy in the afternoon. Diurnal temperature fluctuates over 20F over the day all year.

California Climate Zone 9

Both coastal and interior weather influences the Southern Californian inland valley climate zone. The inland winds bring hot and dry air, and marine air brings cool and moist air. This area is famous for growing citrus because the summers are hot and winters never frost. This area has as many HDD as CDD. Compared to the coast, summers are warmer and winters are cooler. Rain falls in the winter, averaging around 2" per month between November and April. More than 50% of the time skies are clear or partly cloudy (Guide to California Climate Zones, 2011).

Additional cities

More locations were considered in order to expand the analysis, using ASHRAE 90.1 climate zone definitions. Napa, CA is considered to be in ASHRAE climate zone 3C, and Los Angeles, CA is in zone 3B.

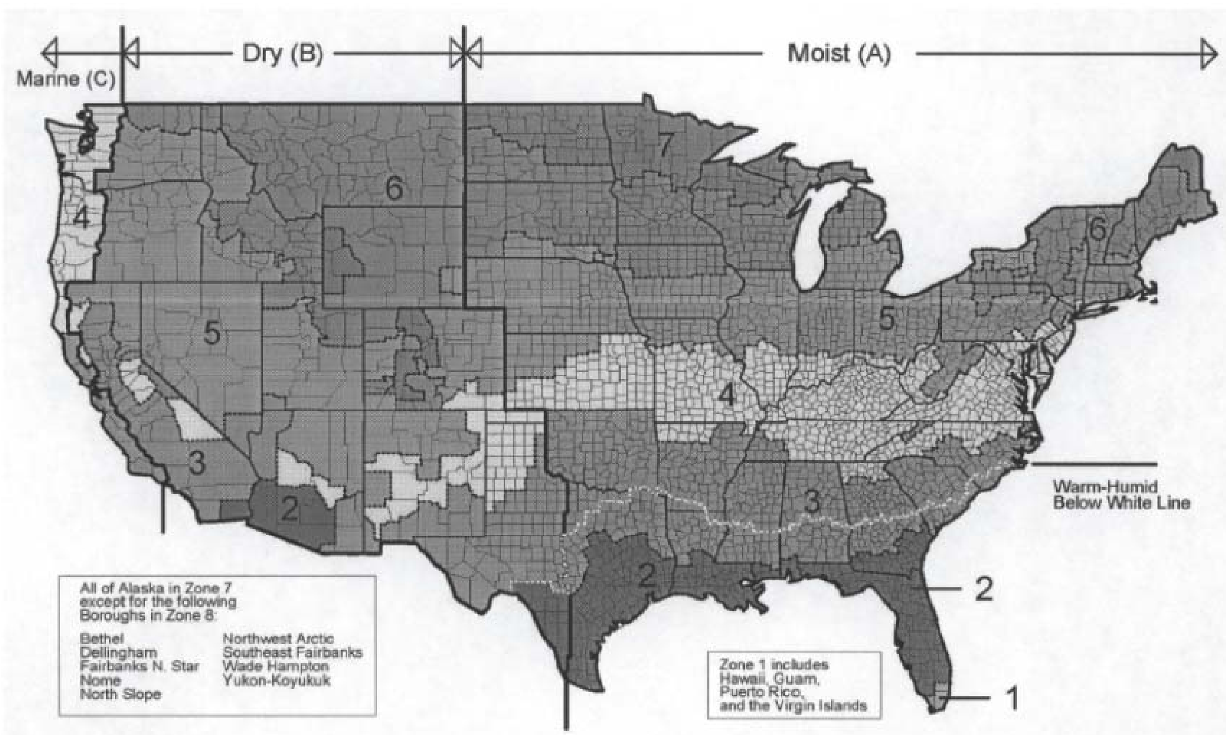


Figure 4: Climate Zones for United States Locations (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.)

Seven additional cities were selected in order to get a broader spectrum of climate types in some of the United States' most populous cities. These cities are outlined along with the original California cities in the table below:

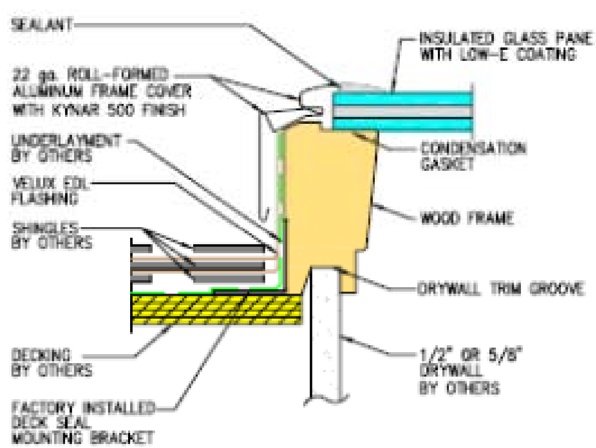
Table 5: Cities by Climate Zone

Zone	Climate Type	City
2A	Hot – Humid	Orlando, FL
3A	Warm – Humid	Dallas, TX
3B	Warm – Dry	Los Angeles, CA
3C	Warm – Marine	Napa, CA
4C	Mixed – Marine	Seattle, WA
5	Cool	Boston, MA
5A	Cool – Humid	Chicago, IL
5B	Cool – Dry	Denver, CO
6A	Cold – Humid	Minneapolis, MN

2.4 Fenestration

Following the California Building Code, the minimum vertical window area allowed for a single family home is 8% of the habitable floor area [1], while the maximum total glazing area (including windows and skylights) is 20% of the total floor area (see Appendix A). This analysis considers these two extremes as well as an average between the two, with window area at 14% of the floor area, in order to consider the full range of possible fenestration combinations.

Figure 5: Skylight Construction



The skylight selected for analysis is VELUX model FS (#VEL-N-18-00001-00001), an Energy Star certified fixed skylight with the following NFRC-rated whole-unit characteristics:

Table 6: Skylight Energy Performance Ratings[2]

Total U-factor	0.44
Solar Heat Gain Coefficient	0.26
Total Visible Transmittance	0.60

Refer to Appendix B for the NFRC label. The skylight is constructed with an aluminum-clad wood frame and high performance ¾" double glazing using Cardinal LoĒ^{3}-366® with argon fill, with the following center of glass values:

[1] 2010 California Residential Code, Title 24, Part 2.5 – Section R303.1
[2] National Fenestration Rating Council

Table 7: Glazing Center-of-Glass Values[3]

Center-of-glass U-factor	0.24
Solar Heat Gain Coefficient	0.27
Visible Transmittance	0.65

Windows for the home were modeled using the same construction and glazing characteristics as the skylight, with the following whole fenestration ratings:

Table 8: Window Energy Performance Ratings[4]

Total U-factor	0.35
Solar Heat Gain Coefficient	0.26
Total Visible Transmittance	0.60

The width of the standard skylight's wood frame is 1.65" [5] (0.138 feet) with a U-factor of 0.53. In order to avoid applying different whole-unit fenestration U-values and SHGC values for different fenestration sizes in the energy model, this analysis has normalized these values based on the standard NFRC-rated skylight size (49" x 49") such that each window and skylight is considered to have 0.1306 square feet of frame area per square foot of fenestration. North and south windows are split into two separate windows on either side of the door (see Appendix B) which also influences the effective frame width.

When applying the fenestration sizes calculated in Section 2.6 – Daylight Factor Calculations, this normalized frame area results in varying frame widths for each parameter's fenestration type and size used in the energy model as follows:

Table 9: Frame area calculations

Model Number	***Skylight Orientation***	***Window Area***	***Vertical Window Distribution***	***Normalized frame width per fenestration (feet)*** Window N/S	Window E/W	Skylight N	Skylight S
1 (Baseline)	None	Maximum (20% window to floor area)	50% N/S, 50% E/W	0.203	0.229	-	-
2			70% N/S, 30% E/W	0.217	0.211	-	-
3	North only	Average (14% window to floor area)	50% N/S, 50% E/W	0.185	0.217	0.202	-
4			70% N/S, 30% E/W	0.202	0.194	0.202	-
5		Minimum (8% window to floor area)	50% N/S, 50% E/W	0.150	0.192	0.229	-
6			70% N/S, 30% E/W	0.172	0.162	0.229	-
7	South only	Average (14% window to floor area)	50% N/S, 50% E/W	0.185	0.217	-	0.202
8			70% N/S, 30% E/W	0.202	0.194	-	0.202
9		Minimum (8% window to floor area)	50% N/S, 50% E/W	0.150	0.192	-	0.229
10			70% N/S, 30% E/W	0.172	0.162	-	0.229

3 Cardinal Glass LoĒ Performance Stats http://www.cardinalcorp.com/technology/reference/loe-performance-stats/
4 National Fenestration Rating Council
5 VELUX FS-01-0008 product data sheet

11	50% North, 50% South	Average (14% window to floor area)	50% N/S, 50% E/W	0.185	0.217	0.164	0.164
12			70% N/S, 30% E/W	0.202	0.194	0.164	0.164
13		Minimum (8% window to floor area)	50% N/S, 50% E/W	0.150	0.192	0.203	0.203
14			70% N/S, 30% E/W	0.172	0.162	0.203	0.203

2.5 Daylight Target

The analysis uses the Daylight Factor (DF) metric in order to determine the varying amount of skylight and vertical windows needed to achieve a well-daylit home. Daylight Factor is defined as the ratio of indoor illuminance at a point to the outdoor horizontal illuminance, under an overcast CIE[6] reference sky, expressed as a percentage. While the Daylight Factor metric is too limiting to truly evaluate the annual daylight level in a building, it was selected as the baseline metric for this analysis because it is not influenced by the orientation of the building or the geographical location, thus allowing consistent baselines and parameters across all cities analyzed.

The daylight factor has long been used as a guide to adequate daylighting, as it is successful in describing how bright a space feels. This analysis uses a target Daylight Factor of 5%, following European recommendations targeting a daylight factor of 5% to achieve a space that is “cheerfully lit” (N. Lukman, B.N. Hibrahim, and S. Hayman, 2002). A 5% daylight factor is also recommended by the British Standards Institution for spaces to not require electric lighting (Christofferson, 2007).

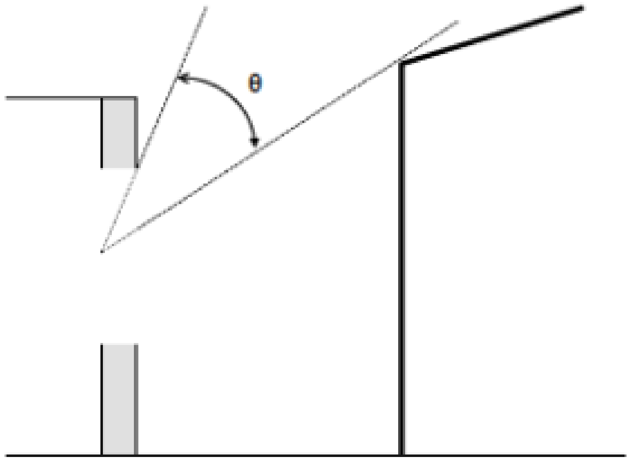
2.6 Daylight Factor Calculation

Daylight factor at any point in a zone is calculated by summing the three daylight contributions: the sky component (SC), externally reflected component (ERC), and internally reflected component (IRC).

$$DF = SC + ERC + IRC$$

A simplified method developed by the Building Research Establishment (Crisp, VHC and Littlefair, PJ, 1984) relates an average Daylight Factor to the vertical glazed area within the zone:

[6] Commission Internationale de L’Eclairage (International Commission on Illumination)



$$DF = t\frac{A_w \theta}{A(1-R^2_{mean})}$$

Figure 6: Daylight Factor Calculation

t = glazing visible transmittance
A_w = Area of the vertical windows
A = total area of ceiling, floor and walls (including window area) in ft2
Θ = angle of the visible sky
R_{mean} = area-weighted reflectance of the ceiling, floor, and walls (including windows)

When this calculation method has been compared to actual side-lit rooms, the formula gave results with a standard error of +/- 10% of the measured values (Lynes, 1979). For these simplified calculations, it has been assumed that there are no visual obstructions, and the wall depth has been ignored, for a Θ = 90°.

When estimating Daylight Factor contribution from skylights, the simplified formula for average daylight factor is the ratio of how much light from the sky reaches the work plane (Laouadi, A. and Atif, M.R., 2000):

$$DF_{skylight} = t \times CU \times A_{skylight} / A_{roof}$$

t = glazing visible transmittance
$A_{skylight}$ = Area of the skylight glazing
A_{roof} = Area of the roof (interior)
CU = Coefficient of Utilization (the fraction of light leaving the skylight that reaches the work surface) – simplified to 1.0

The total average daylight factor can then be estimated as follows:

$$DF_{average} = DF_{window} + DF_{skylight}$$

Using a target daylight factor of 5% for all models, the analysis uses the formulas above and works backwards to derive the vertical window area and skylight area required. These fenestration areas are then distributed on the different façades to meet the parameter requirements (model numbers 1-14). The fenestration area results are as follows:

Table 10: Fenestration Area Calculations

Model Number	*Skylight Orientation*	*Window Area*	*Vertical Window Distribution*	*Calculated Window Area (SF)* N / S	E/W	*Calculated Skylight Area (SF)* N	S	*Total Fenestration Area (SF)*	*Total % Fenestration to Floor Area*
1 (Baseline)	None	Maximum (20% window to floor area)	50% N/S, 50% E/W	99	99	0	0	397	20%
2			70% N/S, 30% E/W	139	60	0	0	397	20%
3	North only	Average (14% window to floor area)	50% N/S, 50% E/W	70	70	49	0	329	16%
4			70% N/S, 30% E/W	98	42	49	0	329	16%
5		Minimum (8% window to floor area)	50% N/S, 50% E/W	40	40	100	0	260	12%
6			70% N/S, 30% E/W	56	24	100	0	260	12%
7	South only	Average (14% window to floor area)	50% N/S, 50% E/W	70	70	0	49	329	16%
8			70% N/S, 30% E/W	98	42	0	49	329	16%
9		Minimum (8% window to floor area)	50% N/S, 50% E/W	40	40	0	100	260	12%
10			70% N/S, 30% E/W	56	24	0	100	260	12%
11	50% North, 50% South	Average (14% window to floor area)	50% N/S, 50% E/W	70	70	25	25	329	16%
12			70% N/S, 30% E/W	98	42	25	25	329	16%
13		Minimum (8% window to floor area)	50% N/S, 50% E/W	40	40	50	50	260	12%
14			70% N/S, 30% E/W	56	24	50	50	260	12%

The calculated areas above result in atypical fenestration sizes. In order to use consistent thermal properties across the energy analysis for all fenestration sizes, properties of these fenestration areas are normalized based on NFRC rated values (see section 2.4 – Fenestration).

Note that as window area decreases, skylight area increases to meet the 5% daylight factor. However less skylight area is required to achieve the same daylight factor as the windows-only runs. The net fenestration area for the "minimum window" runs (model numbers 5, 6, 9, 10, 13, and 14) is 260 sf, which is a 34.5% net fenestration area reduction relative to the "maximum window" runs (model numbers 1 and 2).

The separate daylight factor contributions from windows and skylights were calculated as follows:

Table 11: Daylight Factor Contributions for Windows and Skylights

Model Number	***Skylight Orientation***	***Window Area***	***Vertical Window Distribution***	**Window DF**	**Skylight DF**
1 (Baseline)	None	Maximum (20% window to floor area)	50% N/S, 50% E/W	5.00%	0.00%
2			70% N/S, 30% E/W	5.00%	0.00%
3	North only	Average (14% window to floor area)	50% N/S, 50% E/W	3.52%	1.48%
4			70% N/S, 30% E/W	3.52%	1.48%
5		Minimum (8% window to floor area)	50% N/S, 50% E/W	2.01%	2.99%
6			70% N/S, 30% E/W	2.01%	2.99%
7	South only	Average (14% window to floor area)	50% N/S, 50% E/W	3.52%	1.48%
8			70% N/S, 30% E/W	3.52%	1.48%
9		Minimum (8% window to floor area)	50% N/S, 50% E/W	2.01%	2.99%
10			70% N/S, 30% E/W	2.01%	2.99%
11	50% North, 50% South	Average (14% window to floor area)	50% N/S, 50% E/W	3.52%	1.48%
12			70% N/S, 30% E/W	3.52%	1.48%
13		Minimum (8% window to floor area)	50% N/S, 50% E/W	2.01%	2.99%
14			70% N/S, 30% E/W	2.01%	2.99%

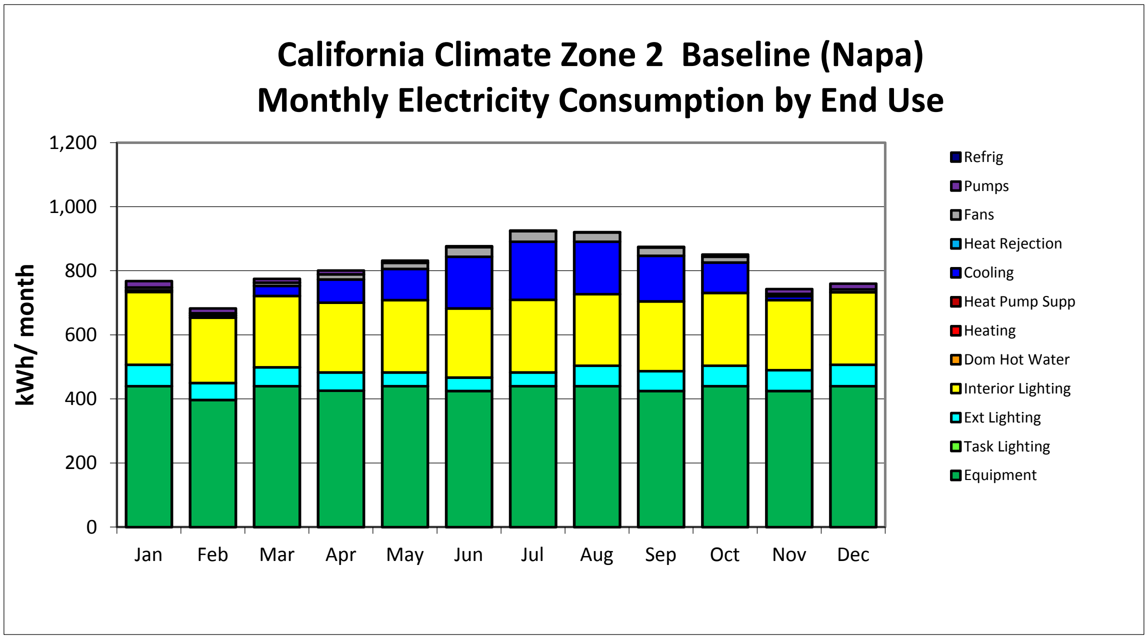
Daylighting models of each parameter were built in AGi32 to support these results, and were found to have a total error of no more than +/- 8.4% from the formula calculations above (average error of 3.07%). Details of the daylighting analysis can be found in Appendix C.

3 Results

The following sections summarize the specifics of the analysis results and breakdown of energy use in the two California climate zones. For additional analysis results for the other seven cities, please refer to Appendix E.

3.1 Baseline models

In each climate zone, model #1 (using the maximum allowable window area) is considered to be the baseline. The baseline models in each climate zone are identical in every respect except for the climate data, the associated weather file, and the utility rates. See Appendix B for more information on the model inputs. The total annual energy use in each climate was calculated using DOE2 software. The results of the California climate zones are illustrated in the charts below.



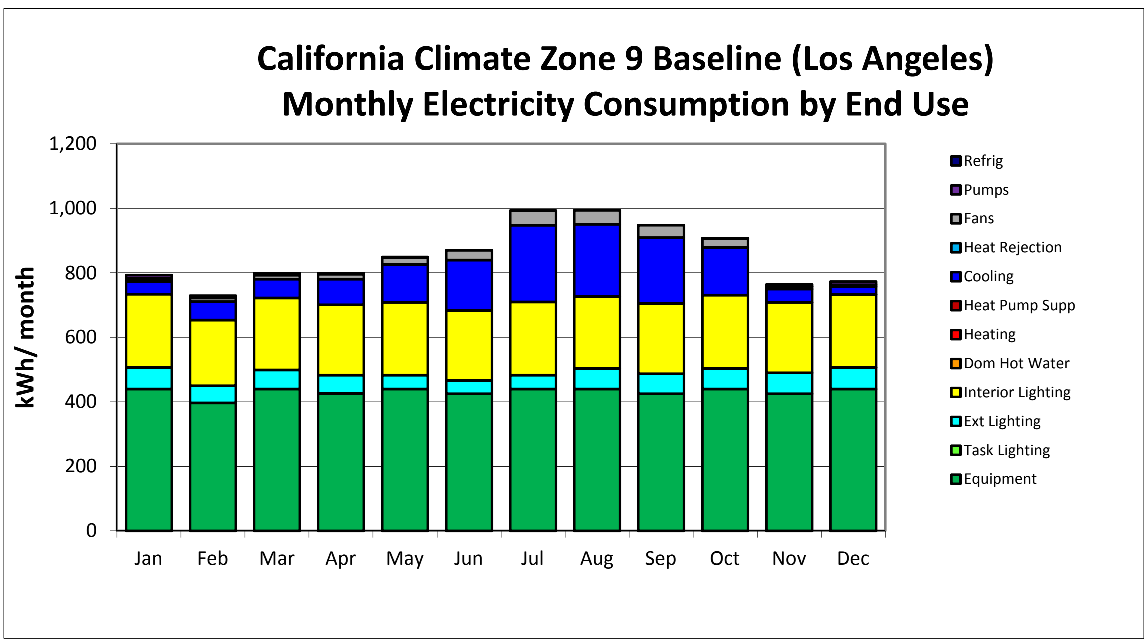
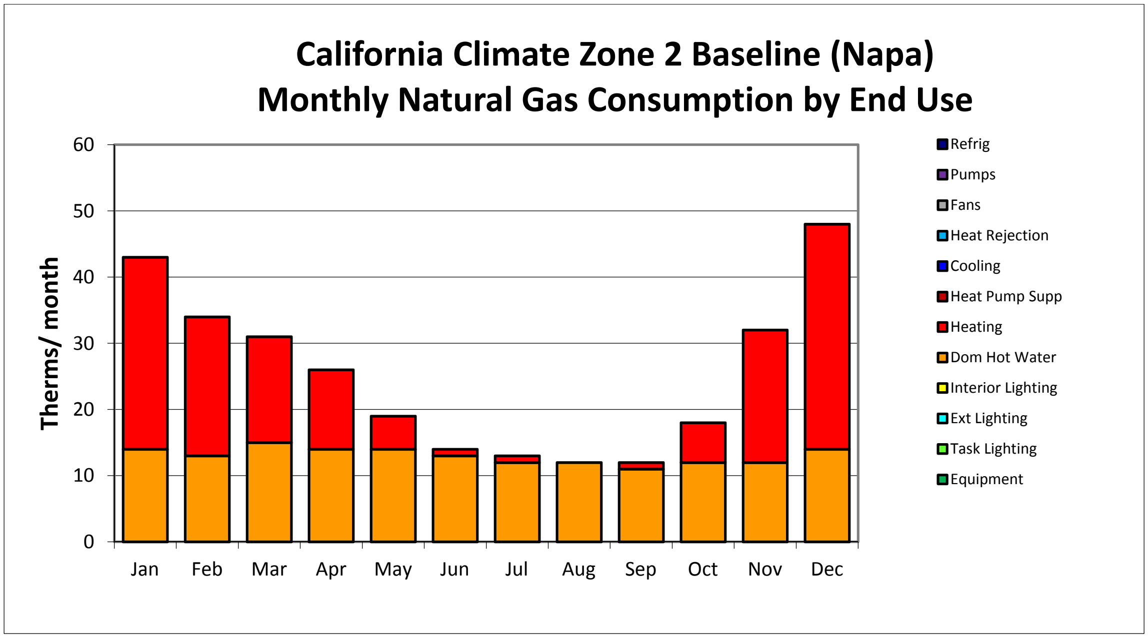


Figure 7: Monthly Baseline Electricity Consumption



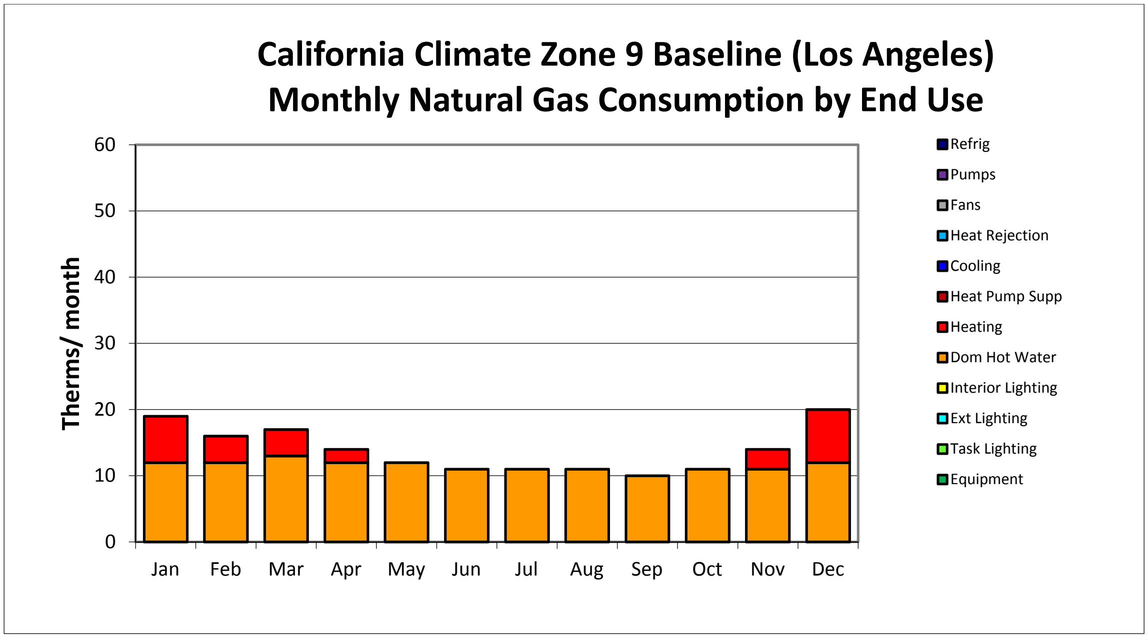


Figure 8: Monthly Baseline Natural Gas Consumption

This analysis considers both energy use and utility costs for the different climate zones. The energy costs for the baseline model in Climate Zone 2 are $2421/year, while the energy costs in Climate Zone 9 are $1689/year. As expected, heating energy required in Napa is much greater than that in Los Angeles.

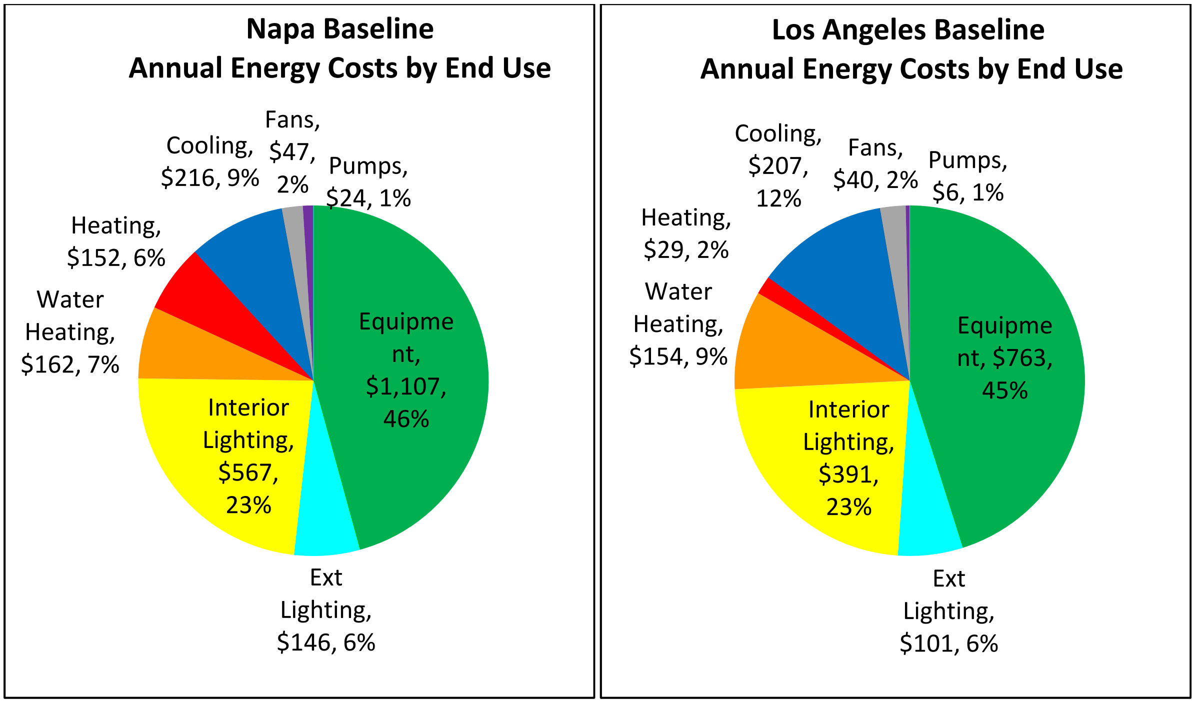


Figure 9: Comparative Energy Costs for the Baseline Model #1

3.2 Parameter Results

In the parametric model runs, the only variables are total fenestration area and distribution on various surfaces. No other energy saving measures are implemented and no lighting energy savings are assumed. The following tables show the results of the energy use and costs for the 14 model runs in each climate.

In every single case in both California climates, the energy use and energy costs are reduced. The model runs in each climate with the highest energy cost savings are highlighted in green. In both climates, the highest savings occurs with model run #6, which has the minimum window area distributed 70% on the north/south and 30% on east/west, along with 100 sf of north-facing skylights.

As the total fenestration area decreases, the skylight area increases. In general, annual energy costs decrease with less total fenestration area with the exception of Climate Zone 9 runs 7-10 (south-facing skylights). The increase in cooling costs with increased south-facing skylight area is more than the reduction in heating costs in this cooling-dominated climate.

In California Climate Zone 2, we have the following observations based upon the modeling results:

- Runs with south skylights have lowest heating costs (7-10)
- Runs with north skylights have lowest cooling costs (3-6)
- Runs with 70/30 distribution of windows have lower energy costs than those with 50/50

In California Climate Zone 9, which is a cooling dominated climate, our observations are changed:

- Variation in heating costs from the highest to lowest is only $9/yr as compared to $22/yr in Climate Zone 2, so heating energy use has less of an influence on the results in this climate zone.
- Runs with south skylights have lowest heating costs (7-10), but the increase in cooling results in higher total energy costs than those with north skylights
- The only instance of savings decreasing by increasing the skylight area in this study occurs in the change from run #8 to run #10 in this climate zone. There are still savings over the baseline run #1, but they are reduced from $11 in run #8 (70/30 window split, 14% window to floor areas, 49 square feet of skylights) to $8 in run #10 (70/30 window split, 8% window to floor areas, 100 square feet of skylights).
- Runs with north skylights have lowest cooling costs (3-6)
- Runs with 70/30 distribution of windows have lower energy costs than those with 50/50

Table 12: Napa: CA Climate Zone 2 Parametric Results

Climate Zone 2 Model Number	*Cost of Electricity*	*Cost of Natural Gas*	*Annual Energy Cost*	*Annual Savings Relative to Model 1*	*Electricity Use (kWh)*	*Electricity Savings Relative to Base (kWh)*	*Natural Gas Use (Dtherms)*	*Natural Gas Savings Relative to Base (Dtherms)*
1 - BASELINE	$2,105	$316	$2,421	-	9,812	0	30	0
2	$2,077	$314	$2,391	$30	9,729	83	30	0
3	$2,086	$318	$2,404	$17	9,755	57	30	0
4	$2,065	$316	$2,381	$40	9,693	119	30	0
5	$2,068	$322	$2,390	$31	9,702	110	31	-1
6	$2,056	$321	$2,377	$44	9,665	147	31	-1
7	$2,104	$309	$2,413	$8	9,807	5	30	0
8	$2,084	$307	$2,391	$30	9,748	64	29	1
9	$2,104	$301	$2,405	$16	9,808	4	29	1
10	$2,092	$300	$2,392	$29	9,773	39	29	1
11	$2,094	$314	$2,408	$13	9,778	34	30	0
12	$2,074	$312	$2,386	$35	9,718	94	30	0
13	$2,085	$312	$2,397	$24	9,751	61	30	0
14	$2,073	$311	$2,384	$37	9,715	97	30	0

Table 13: Los Angeles: CA Climate Zone 9 Parametric Results

Climate Zone 9 Model Number	Cost of Electricity	Cost of Natural Gas	Annual Energy Cost	Annual Savings Relative to Model 1	Electricity Use (kWh)	Electricity Savings Relative to Base (kWh)	Natural Gas Use (Dtherms)	Natural Gas Savings Relative to Base (Dtherms)
1 - BASELINE	$1,505	$184	$1,689	-	10,218	0	17	0
2	$1,492	$183	$1,675	$14	10,141	77	17	0
3	$1,491	$186	$1,677	$12	10,134	84	17	0
4	$1,481	$185	$1,666	$23	10,078	140	17	0
5	$1,478	$189	$1,667	$22	10,055	163	17	0
6	$1,472	$189	$1,661	$28	10,021	197	17	0
7	$1,505	$182	$1,687	$2	10,217	1	16	1
8	$1,496	$182	$1,678	$11	10,163	55	16	1
9	$1,506	$181	$1,687	$2	10,223	-5	16	1
10	$1,501	$180	$1,681	$8	10,191	27	16	1
11	$1,497	$185	$1,682	$7	10,172	46	17	0
12	$1,488	$184	$1,672	$17	10,117	101	17	0
13	$1,491	$185	$1,676	$13	10,132	86	17	0
14	$1,485	$184	$1,669	$20	10,100	118	17	0

3.3 Time Dependent Value Analysis

Time Dependent Value, or TDV, is a way to evaluate energy efficiency measures that can better reflect the actual costs to users, utility, and society over the life of the building (Time Dependent Valuation of Energy for Developing Building Efficiency Standards, 2011). Over time, designing with this long-term valuation in mind can lead to significant cost savings for both building owners and the utility system, along with improved utility reliability.

TDV is based on a series of 8760 values of energy cost, one for each hour of a typical year. The hourly valuation of kBtu is different in each climate zone, but uses an average cost of $0.17318/kBtu for residential buildings, and totals the weighted energy costs over a lifecycle of 30 years. These 30 year totals are represented in 2011 dollars.

The results of the TDV analysis in each climate tell a very different story than the flat utility costs. In the TDV analysis, greater weight is given to the cost of natural gas over the lifetime of the building, so the different effects of north and south skylights are more pronounced. Each parameter still results in an overall energy cost savings.

Table 14: TDV Analysis - 30 year Lifecycle – Napa, CA Climate Zone 2

Model Number	*TDV Lifecycle Electricity Costs*	*TDV Electricity Savings Relative to Model 1*	*TDV Lifecycle Gas Costs*	*TDV Gas Savings Relative to Model 1*	*TDV Total savings Relative to Model 1*
1 - BASELINE	$40,506	-	$8,795	-	
2	$40,065	$441	$8,724	$71	$512
3	$40,238	$267	$8,880	($86)	$182
4	$39,917	$588	$8,811	($17)	$572
5	$40,000	$506	$8,993	($198)	$307
6	$39,805	$700	$8,946	($151)	$549
7	$40,478	$28	$8,594	$200	$228
8	$40,170	$336	$8,538	$256	$592
9	$40,491	$15	$8,370	$425	$440
10	$40,312	$194	$8,335	$459	$653
11	$40,347	$159	$8,755	$39	$198
12	$40,037	$469	$8,694	$101	$569
13	$40,232	$273	$8,695	$99	$373
14	$40,045	$461	$8,657	$138	$599

Under the TDV lifecycle cost valuation, the best energy savings in Climate Zone 2 are seen with model #10, which uses skylights on the south only, with windows split 70/30. The second highest savings in this zone are seen in model run #14, which also has the 70/30 split windows, and skylights split evenly between the north and south.

This type of analysis illustrates that while cooling savings are important, the solar heat gain from fenestration has a distinct contribution to heating energy savings. Introducing skylights on the north side only, as seen in runs 3-6, generates an increase in heating costs.

Model run #6, which had the greatest energy cost savings in the flat cost analysis, falls into a distant 6th place in the TDV analysis. It still has the highest cooling savings, but the increase in heating energy outweighs the benefits of the cooling savings.

Table 15: TDV Analysis - 30 year Lifecycle – Los Angeles, CA Climate Zone 9

Model Number	*TDV Lifecycle Electricity Costs*	*TDV Electricity Savings Relative to Model 1*	*TDV Lifecycle Gas Costs*	*TDV Gas Savings Relative to Model 1*	*TDV Total savings Relative to Model 1*
1 - BASELINE	$33,683	-	$3,970	-	
2	$33,413	$270	$3,927	$43	$313
3	$33,419	$264	$4,056	($86)	$178
4	$33,222	$461	$4,019	($49)	$412
5	$33,169	$514	$4,160	($190)	$324
6	$33,049	$634	$4,133	($163)	$471
7	$33,668	$15	$3,913	$56	$71
8	$33,483	$200	$3,880	$90	$291
9	$33,683	$0	$3,853	$117	$117
10	$33,569	$114	$3,834	$136	$249
11	$33,533	$150	$3,992	($22)	$129
12	$33,343	$340	$3,951	$19	$359
13	$33,406	$277	$4,004	($34)	$243
14	$33,290	$393	$3,982	$138	$530

In Climate Zone 9, which is more cooling dominated than Climate Zone 2, the greatest savings are now seen in model run #14, with skylights split evenly between north and south. Run #6, which had the highest energy cost savings, and has skylights only on the north, falls into second place.

It is very interesting to see the TDV analysis reveals a clear change in heating energy costs in this climate zone as the skylight orientations change. There is a distinct increase in heating energy with north-facing skylights (runs 3-6) and heating savings with south-facing skylights (runs 7-10).

3.4 Annual Daylight

While daylight illuminance in homes is not as critical as in a task-based setting such as an office, there is a concern that daylight quality or quantity could be affected by reducing the total glazing area, which could in turn lead to higher lighting energy use. To address this concern, a second daylighting analysis was performed on three of the model cases using Ecotect accompanied by Radiance and Daysim. The daylight analysis compares the amount of daylight achieved and glare present throughout the course of a year in three different models (baseline, #6, and #14) in the two California cities.

This analysis first calculated an annual climate-based metric called ***daylight autonomy***. Daylight autonomy (DA) is a measure of the percentage of the number of hours that a particular daylight level is reached or exceeded throughout the year (The Lighting Handbook, Tenth Edition, 2011). Since this metric only includes the time that a particular illuminance is exceeded, it provides a measure of the potential of daylight to replace electric lighting. It is also used to evaluate general daylight coverage across a space.

Another annual metric considered is ***Useful Daylight Illuminance*** (UDI). This metric calculates the total number of hours that the illuminance at a point falls into typical illuminance ranges. The ranges are usually <10 FC (100 lux), 10-200 FC (100-2000 lux), and >200 FC (2000 lux). The most useful daylight typically occurs in the middle range. Less than 10 FC is considered insufficient; more than 200 FC is likely to contribute to higher levels of glare (The Lighting Handbook, Tenth Edition, 2011).

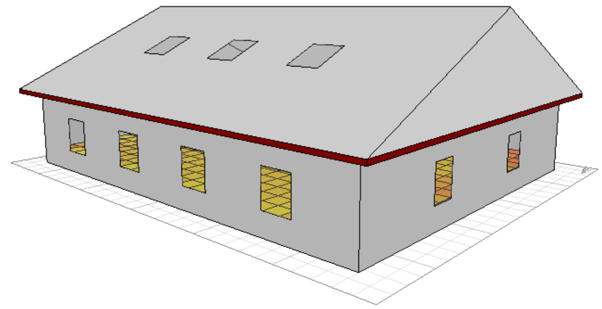


Figure 10: Ecotect/Daysim model

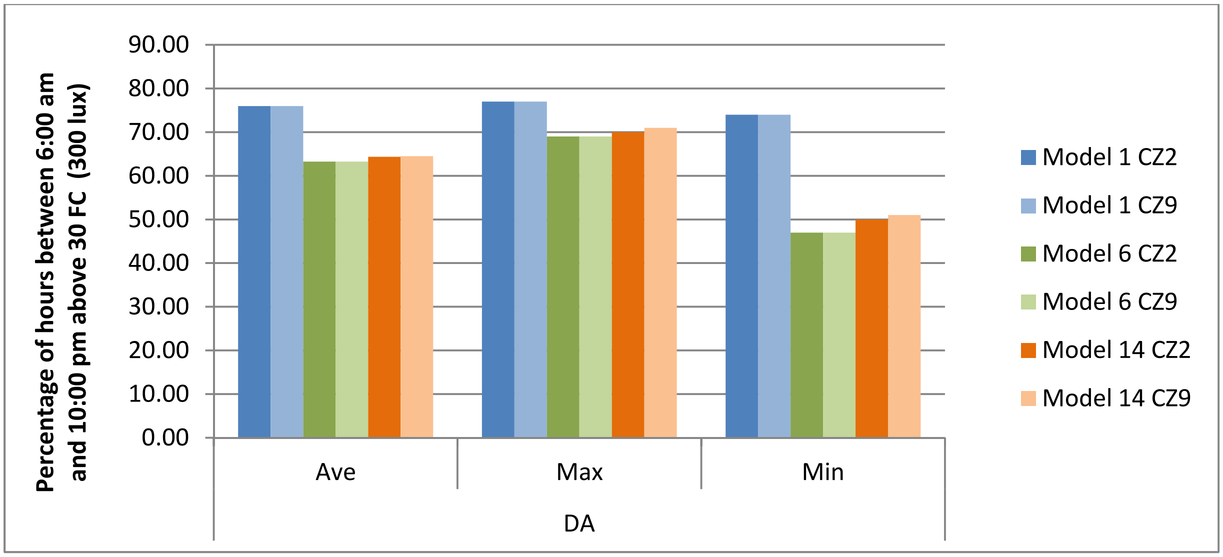
The "usefulness" of the middle UDI range is based on surveys carried out in non-residential, largely office buildings where daylight glare on visual display devices can be troublesome (Mardaljevic, 2010). Since tasks in the residential setting do not always match that of the office, so it has been argued that in residential spaces, the useful UDI range could be increased to 250 FC (2500 lux) (Mardaljevic, 2010). However since the software used in this analysis (Daysim) assumes that blinds or shades are used to block most direct sunlight, the standard range of 10-200 FC (100-2000 lux) is used.

For the DA and UDI analysis of this project, the target illuminance is set at 30 footcandles (300 lux), and the time range is set at 6:00 am to 10:00 pm, in order to view the greatest potential of daylight throughout the year. The three models analyzed were #1 (Baseline), #6 (lowest energy user), and #14 (minimum glazing, even skylight distribution), with calculation points on a 2 foot grid. Each model was analyzed in both California climate zones for a total of six runs.

Daylight Autonomy

The table below summarizes the average, maximum, and minimum daylight autonomy percentage values calculated over the grid points in the six total runs.

Table 16: Daylight Autonomy Summary



The results show that Model 1 (all windows, no skylights) has the highest percentage of average, maximum, and minimum daylight autonomy using the above criteria. In other words, each point in the house reaches 30 FC (300 lux) or more for the greatest percentage of hours. This makes logical sense, since Model 1 captures more low angles of sunlight on the east and west than either of the other models, which results in a higher number of daylit hours. Model 1 has the same glazing area on each orientation, and this creates more uniform daylight autonomy across the calculation grid as the sun moves around the building. It also follows that Model 6 (minimum windows, skylights only on the north) should have the lowest average DA, as the glazing area is the least evenly distributed.

Useful Daylight Illuminance

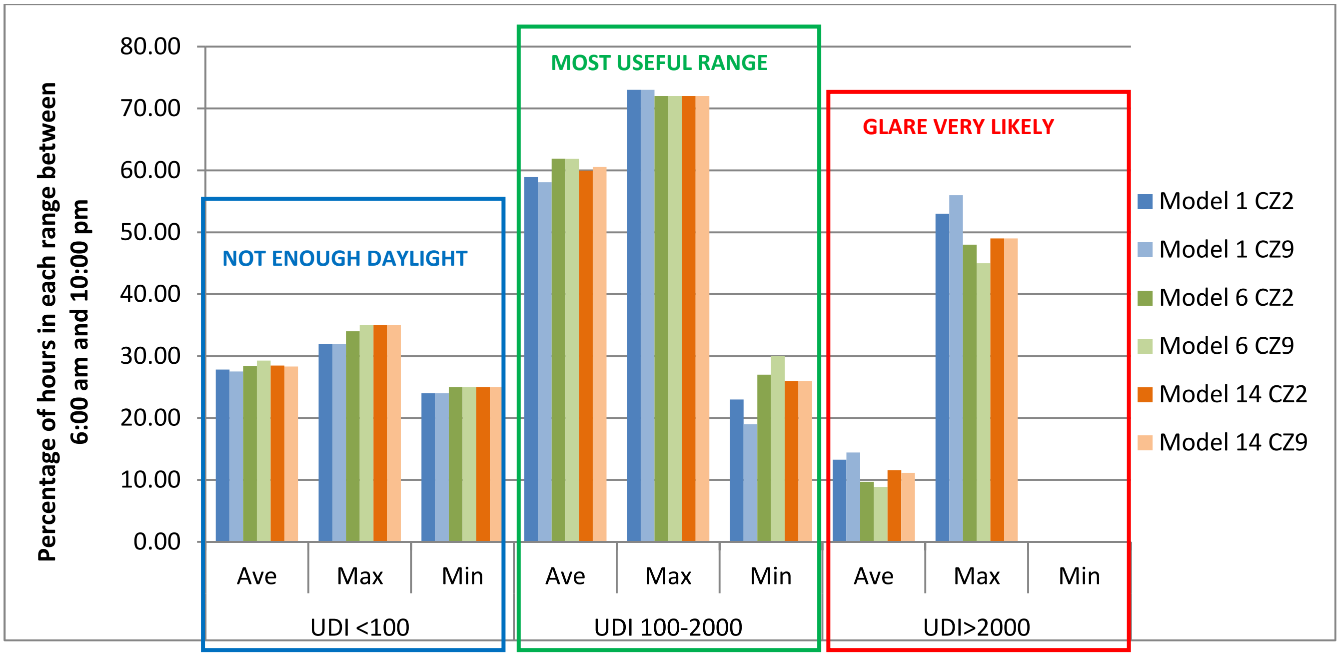
The table below summarizes the calculated average, maximum, and minimum useful daylight illuminance (UDI) percentage values in each UDI category over the grid points in the six total runs. The categories are described as follows:

UDI<100: The percentage of hours that a calculation point has less than 10 FC (100 lux). Daylight is considered insufficient in this range.

UDI 100-2000: The percentage of hours that a calculation point has between 10-200 FC (100-2000 lux). This is considered to be the most useful daylight range.

UDI>2000: The percentage of hours that a calculation point has greater than 200 FC (2000 lux). This is the range at which glare is likely to be a problem.

Table 17: Useful Daylight Illuminance Summary



However, the analysis of useful daylight illuminance as illustrated above is rather different. The UDI comparison shows that Model 6 has the highest average percentage of hours in the most useful daylight range, UDI 100-2000, or that between 10-200 FC (100-2000) lux. Model 6 also has the highest minimum, showing that the useful daylight is also the most even between the three. This is due to the greater contribution of daylight from north-facing skylights. Model 14, which uses an even distribution of north and south skylights, has the second highest average useful daylight illuminance.

In the high range UDI>2000, which is typically indicative of present glare, Model 1 (windows only) has the highest percentage of hours by far. Model 6 has the lowest average in this range, indicative of the lowest propensity for glare. Model 14, with an even split of north/south skylights, is the second lowest in this range.

The results between the two California climate zones are roughly similar for both metrics.

APPENDIX A – Building Code and Site Details by City

Table 18: Code Name and Utility Rate Structures by City*

City:	Building Code	Energy Code	Details on electric rates	Details on gas rates
NAPA (CA-CZ2)	California Building Code 2011	California Title 24 Energy Code 2010, Package D	PG&E Tiered Residential: • Summer Tier 1 (0-330 kWh): $0.12/kWh • Summer Tier 2 (331-429 kWh): $0.14/kWh • Summer Tier 3 (430-660 kWh) : $0.30/kWh • Summer Tier 4 (661+ kWh): $0.34/kWh • Winter Tier 1 (0-351 kWh): $0.12/kWh • Winter Tier 2 (352-456 kWh): $0.14/kWh • Winter Tier 3 (457-702 kWh): $0.30/kWh • Winter Tier 4 (703+ kWh): $0.34/kWh	PG&E: $1.04579/therm
LOS ANGELES (CA-CZ9)	California Building Code 2011	California Title 24 Energy Code 2010, Package D	City of Burbank Water & Power: • Tier 1 (0-250 kWh): $0.1124/kWh • Tier 2 (250-750 kWh): $0.1502/kWh • Tier 3 (751+ kWh): $0.1713/kWh	Southern California Gas: $0.16438/day + $0.7465/therm
BOSTON	Massachusetts State Building Code for One- and Two-Family Dwellings, amended 7th Ed.	MA Stretch Code: 2009 IECC with MA Amendments	Nstar: Residential A1 $6.43/month + $0.08015/kWh	Nstar: $12/month + $0.7010/therm
CHICAGO	Chicago Building Code	Chicago Energy Conservation Code	ComEd/Exelon: $17.14/month + $0.08371/kWh summer, $0.08203/kWh winter	Peoples Gas: $19.38/month + $0.4190/th gas + $0.33372/th dist (for 1st 50 therms), $0.12360/th (over 50 th)
DALLAS	2006 International Residential Code with Dallas Amendments	Dallas Energy Conservation Code" - 2009 IECC with Dallas Amendments	Xcel (June-Sept): $6/month + $0.095167/kWh (Oct-May): $0.084967/kWh	Atmos: RRC Tariff No 24126 - $17.28/month + $0.7055/therm
DENVER	2009 International Residential Code	2009 IECC	Xcel: $6.87/month, (Tier 1 + Winter) $0.08826/kWh, or (Tier 2) $0.13301/kWh. Tier 1 = summer first 500 kWh	Xcel: $11.73/month + $0.62742/therm
ORLANDO	Florida Building Code Residential 2010	Florida Building Code, Energy Conservation 2010	OUC: $8/month + $0.06975/kWh (1st 1,000 kWh) $0.07975/kWh (additional kWh over 1,000)	People Gas: $12/month + $0.26782/therm dist + $0.80606/therm PGA = $1.07388/therm
SEATTLE	Seattle Residential Code	2009 Seattle Energy Code (2009 WSEC w/ 2009 Seattle amendments)	Seattle City Light: $3.62/month + $0.0476/kWh (first 10 kWh/day) + $0.0987/kWh (additional)	Puget Sound Energy: $10/month + $0.37372/th delivery + $0.67838/th gas = $1.02562/th

City:	Building Code	Energy Code	Details on electric rates	Details on gas rates
MINNEAPOLIS	Minnesota State Building Code	2006 IECC (with Minnesota Amendments)	Xcel: $6.65/month + $0.07363/kWh summer (June-Sept), $0.06365/kWh winter	Xcel: $9/month + $0.78202/therm April-Oct, $0.8398/therm Nov-March

*Utility rates are current as of February, 2012

Table 19: Building and Energy Code Requirements by City

City:	Wall min R	Roof min R	Window max U	Skylight max U	Fenestration max SHGC	Min % Window to Floor area	Max % Window to Floor area	Max % skylight of roof area	Air-cooled air conditioner EER <135,000 BTU/H	Furnace AFUE <225,000
NAPA (CA-CZ2)	R-13 (wood-framed) U-0.089	R-30 batt in wood framed attic - U-0.034	0.4	0.4	0.4	not less than 8% floor area	20% (includes skylight area). Not more than 5% on the west.	included in max % window area	11.2 EER - EIR=0.2539	78% AFUE or 80% eff
LOS ANGLELES (CA-CZ9)	R-13 (wood-framed) U-0.089	R-30 batt in wood framed attic - U-0.034	0.4	0.4	0.4	not less than 8% floor area	20% (includes skylight area). Not more than 5% on the west.	included in max % window area	11.2 EER - EIR=0.2539	78% AFUE or 80% eff
BOSTON	R-19 (wood framed) - U-0.067	R-38 batt in wood framed attic - U-0.027	0.35	0.6	none	not less than 8% floor area	none	none	13.0 SEER, EIR=0.2527	78% AFUE or 80% eff
CHICAGO	R-19 or R-13 + R-5 (wood framed) - 0.067	R-49 batt in wood framed attic - U-0.021	0.35	0.6	none	not less than 8% floor area	none	none	Federal efficiency standard (National): SEER = 13, EIR=0.2527	Federal efficiency standard (Northern Region): AFUE=81%
DALLAS	R-13 (wood framed) U-0.089	R-30 batt in wood framed attic - U-0.034	0.5	0.65	0.3 (windows and skylights)	not less than 8% floor area	15% (includes skylights area - higher % allowed via performance method)	included in max % window area	Federal efficiency standard (Southeastern Region): SEER = 14, EIR=0.2327	Federal efficiency standard (National): AFUE=81%
DENVER	R-20 or R-13+R-5 rigid c.i. (wood-framed) - U-0.065	R-38 wood framed attic - U-0.027	0.35	0.6	none	not less than 8% floor area	none	none	Federal efficiency standard (National): SEER = 13, EIR=0.2527	Federal efficiency standard (Northern Region): AFUE=81%
ORLANDO	R-13 (wood-framed) U-	R-30 batt in wood	0.65	0.75	0.5 weighted	not less than 8%	20% (includes skylight area)	included in max %	11.2 EER - EIR=0.2539	78% AFUE or 80% eff

	0.089	framed attic - U-0.034			average by area	floor area		window area		
SEATTLE	R-21 (wood framed) - U-0.063	R-49 batt in wood framed attic - U-0.021	0.32	0.5	none	not less than 8% floor area	25% (Climate zone 1, path II option)	included in max % window area	11.2 EER - EIR=0.2539	78% AFUE or 80% eff
MINNEAPOLIS	R-19 or R-13 + R-5 (wood framed) - 0.067	R-38 wood framed attic - U-0.027	0.35	0.6	none	not less than 8% floor area	none	none	Federal efficiency standard (National): SEER = 13, EIR=0.2527	Federal efficiency standard (Northern Region): AFUE=81%

Table 20: Weather and Site Data by City

City:	Weather File	Latitude	Longitude	Elevation	HDD (65)	CDD (50)	Climate Zone (90.1-2007)
NAPA (CA-CZ2)	CZ2\CZ02.bin	38.40 N	122.70W	167 ft	2844	3463	3C
LOS ANGLELES (CA-CZ9)	CZ2\CZ09.bin	34.20 N	118.35 W	699 ft	1458	4777	3B
BOSTON	TMY2\BOSTONMA.bin	42.37 N	71.03 W	20 ft	5641	2897	5
CHICAGO	TMY2\CHICAGIL.bin	41.73 N	87.77 W	620 ft	6176	3251	5A
DALLAS	TMY2\FORT-WTX.bin	32.85 N	96.85 W	440 ft	2259	6587	3A
DENVER	TMY\DENVERCO.bin	39.77 N	104.87 W	5286 ft	6020	2732	5B
ORLANDO	TMY\ORLANDFL.bin	28.43 N	81.33 W	91 ft	686	8227	2A
SEATTLE	TMY2\SEATTLWA.bin	47.65 N	122.30 W	20 ft	4611	2120	4C
MINNEAPOLIS	TMY2\MINNEAMN.bin	44.89 N	93.23 W	980 ft	7981	2680	6A

APPENDIX B – Energy Modeling Inputs

The EQuest 3.6 interface for DOE-2.2 building energy simulation program was used for the building energy analysis. The two figures below show sketches of the eQuest model building envelope geometry and zoning. The geometry is typically simplified for modeling purposes to accurately simulate energy transfer through all surfaces in the building. Windows or skylights on the same orientation and zone are often grouped together to decrease simulation time; this does not affect results of the model.

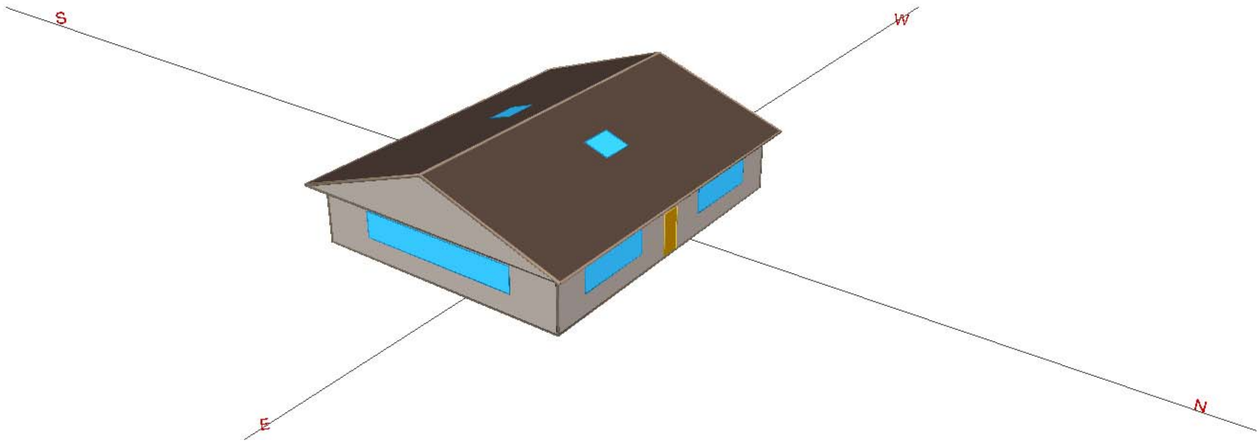


Figure 11: EQuest Sketch of Energy Model

Figure 12: Thermal Zoning

Table 21: Building Envelope Model Inputs

Element	Modeled
Conditioned Floor Area	2,000 SF
Unconditioned Floor Area	none
Above Grade Stories	1
Below Grade Stories	0
Floor-to-Ceiling Height	9'-0"
Roof	
Construction Type	Wood framed attic
Insulation	By code*
Total U-Factor	By code*
Exterior Walls	
Construction Type	Wood frame 16" on center
Insulation	By code*
Total U-Factor	By code*
Ground Floor	
Construction Type	Slab on grade
Insulation	none
Total F-Factor	F-0.038
Fenestration	
Window Type	operable double pane
Whole Window U-Factor	U-0.35
Whole Window SHGC	SHGC-0.26
Skylight Type	Fixed double pane
Whole Skylight U-Factor	U-0.44
Whole Skylight SHGC	SHGC-0.26
Center-of-Glass Performance (both)	U-0.24, SHGC-0.27
Frame Type (both)	Wood with aluminum cladding
Frame U-Factor (both)	U-0.53

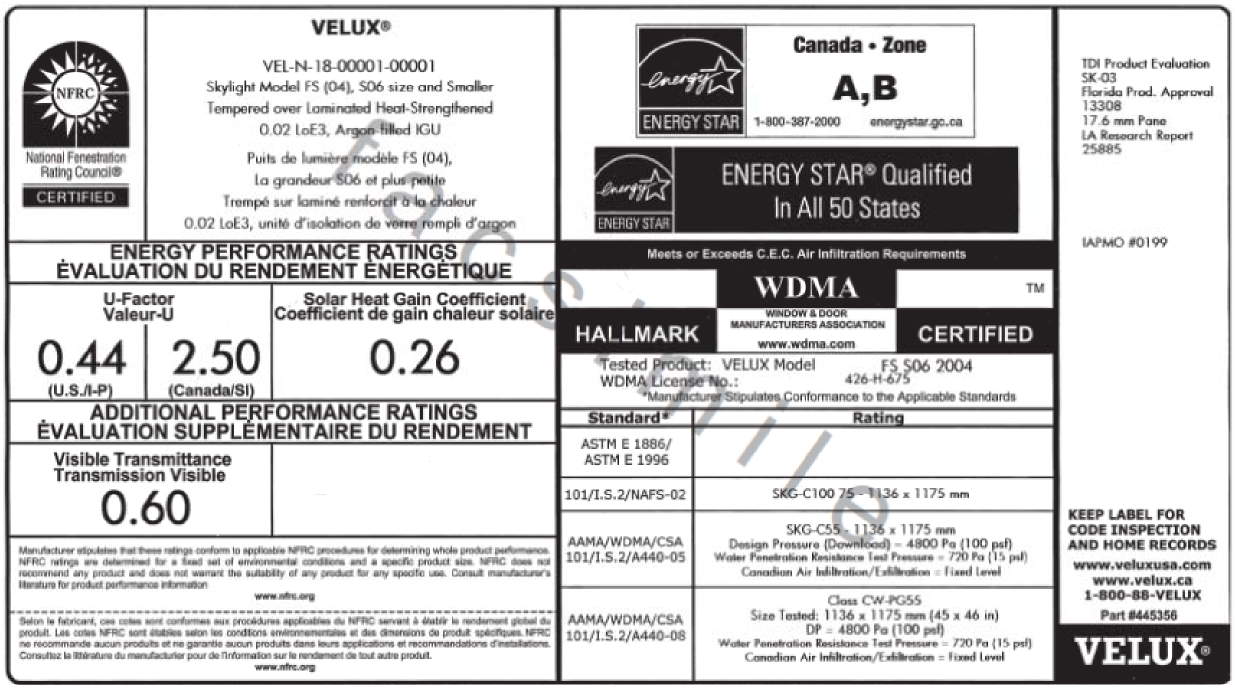
*Refer to Appendix A for code details

Table 22: HVAC and Lighting Model Inputs

Element	Baseline Building (ASHRAE 90.1 - 2004)
Primary System Type	Residential system: Gas-fired furnace and DX air conditioner
Air-Side	
Supply Fan Control	Intermittent
Return Air Path	Ducted
Fan Power	1.0 inWg, 53% fan efficiency
Ventilation Air (cfm)	1162
Heating	
Space Setpoints	70°F, setback to 66°F
Heating Equipment	Gas-fired furnace
Heating Efficiency	By code*
Cooling	
Space Setpoints	76°F, setback to 80°F
Cooling Equipment	split DX
Cooling Efficiency	By code*
Modeled EIR	By code*
Water Heating	
DHW Equipment	natural gas water heater
DHW Heating Efficiency	By code*
DHW Loop Temperature	110° F
Lighting	
Lighting Power (peak W/ft^2)	0.61 W/SF on for 750 hours per year
Daylighting Controls	none
Occupancy Sensors	none
Exterior Lighting (peak kW)	0.20 kW
Loads	
Elect. Equipment (W/ft^2)	0.35 W/SF
Cooking Equipment (W/ft^2)	0.085 W/SF
Refrigeration Equipment (W/ft^2)	0.170 W/SF
Occupancy	4 people

*Refer to Appendix A for code details

Figure 13: Skylight NFRC label



APPENDIX C – Daylight Factor Modeling Results

Each model parameter was built in AGi32 to verify and support the daylight factor methodology. Calculations were run under CIE Sky Type 3 on September 21 at noon. Windows and skylights were distributed equally along surfaces. The average DF calculated by AGi32 = 5.15% (error of 3.07% relative to the target DF = 5%).

Figure 14: Typical AGi32 Daylighting Model

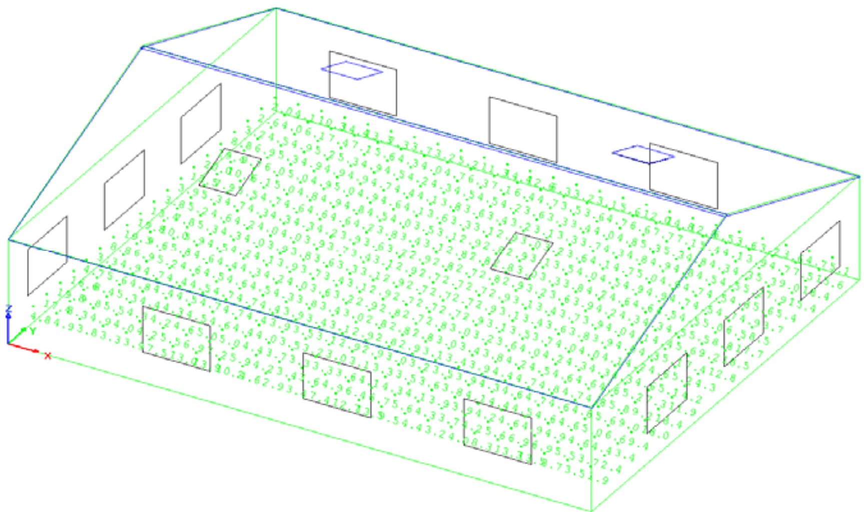


Table 23: AGi32 Daylighting Model Results Relative to Hand Calcs

Model Number	WINDOWS			SKYLIGHTS			TOTAL		
	Formula	AGi32	ERROR	Formula	AGi32	ERROR	Formula	AGi32	ERROR
1	5.00%	4.93%	1.40%	0.00%	0.00%	0.00%	5.00%	4.93%	1.40%
2	5.00%	4.76%	4.80%	0.00%	0.00%	0.00%	5.00%	4.76%	4.80%
3	3.52%	3.74%	6.16%	1.48%	1.35%	8.60%	5.00%	5.09%	1.80%
4	3.52%	3.61%	2.47%	1.48%	1.34%	9.28%	5.00%	4.95%	1.00%
5	2.01%	2.20%	9.28%	2.99%	3.18%	6.46%	5.00%	5.38%	7.60%
6	2.01%	2.10%	4.32%	2.99%	3.18%	6.46%	5.00%	5.28%	5.60%
7	3.52%	3.74%	6.16%	1.48%	1.35%	8.60%	5.00%	5.09%	1.80%
8	3.52%	3.61%	2.47%	1.48%	1.34%	9.28%	5.00%	4.95%	1.00%
9	2.01%	2.20%	9.28%	2.99%	3.18%	6.46%	5.00%	5.38%	7.60%
10	2.01%	2.10%	4.32%	2.99%	3.18%	6.46%	5.00%	5.28%	5.60%
11	3.52%	3.74%	6.16%	1.48%	1.51%	2.23%	5.00%	5.25%	5.00%
12	3.52%	3.61%	2.47%	1.48%	1.48%	0.20%	5.00%	5.09%	1.80%
13	2.01%	2.20%	9.28%	2.99%	3.22%	7.80%	5.00%	5.42%	8.40%
14	2.01%	2.10%	4.32%	2.99%	3.20%	7.13%	5.00%	5.30%	6.00%

Average error:	5.21%	5.64%	4.24%

APPENDIX D – Annual Daylight Modeling Results

Models 1, 6, and 14 in the two California cities were built in Ecotect and then simulated in Radiance and Daysim to evaluate Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). Values were calculated on a 2' grid, with results as follows.

Table 24: Daylight Modeling Summary

Model Type and Climate Zone		DA			UDI <100 lux			UDI 100-2000 lux			UDI>2000 lux		
		Ave	*Max*	*Min*	*Ave*	*Max*	*Min*	*Ave*	*Max*	*Min*	*Ave*	*Max*	*Min*
Model 1	CZ2	75.99	77.00	74.00	27.82	32.00	24.00	58.90	73.00	23.00	13.25	53.00	0.00
Model 1	CZ9	75.99	77.00	74.00	27.51	32.00	24.00	58.08	73.00	19.00	14.44	56.00	0.00
Model 6	CZ2	63.24	69.00	47.00	28.42	34.00	25.00	61.88	72.00	27.00	9.70	48.00	0.00
Model 6	CZ9	63.24	69.00	47.00	29.28	35.00	25.00	61.86	72.00	30.00	8.86	45.00	0.00
Model 14	CZ2	64.37	70.00	50.00	28.46	35.00	25.00	59.94	72.00	26.00	11.57	49.00	0.00
Model 14	CZ9	64.49	71.00	51.00	28.31	35.00	25.00	60.54	72.00	26.00	11.14	49.00	0.00

APPENDIX E – Energy Modeling Results

Table 25: Annual Energy Costs by City

	ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
ASHRAE 90.1 Climate Zone	2A	3A	3B	3C	4C	5	5A	5B	6A
Model:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	$1,203	$1,467	$1,689	$2,421	$1,398	$1,411	$1,580	$1,487	$1,528
2	$1,199	$1,459	$1,675	$2,391	$1,391	$1,405	$1,575	$1,475	$1,520
3	$1,199	$1,464	$1,677	$2,404	$1,390	$1,408	$1,576	$1,487	$1,524
4	$1,197	$1,459	$1,666	$2,381	$1,386	$1,405	$1,573	$1,480	$1,519
5	$1,196	$1,463	$1,667	$2,390	$1,381	$1,407	$1,573	$1,489	$1,519
6	$1,194	$1,459	$1,661	$2,377	$1,379	$1,404	$1,572	$1,484	$1,516
7	$1,202	$1,464	$1,687	$2,413	$1,386	$1,403	$1,576	$1,481	$1,515
8	$1,199	$1,459	$1,678	$2,391	$1,382	$1,399	$1,574	$1,473	$1,510
9	$1,201	$1,462	$1,687	$2,405	$1,373	$1,396	$1,574	$1,476	$1,502
10	$1,199	$1,458	$1,681	$2,392	$1,371	$1,393	$1,572	$1,471	$1,500
11	$1,201	$1,464	$1,682	$2,408	$1,388	$1,407	$1,576	$1,485	$1,520
12	$1,198	$1,458	$1,672	$2,386	$1,384	$1,402	$1,574	$1,477	$1,515
13	$1,198	$1,461	$1,676	$2,397	$1,378	$1,402	$1,573	$1,483	$1,511
14	$1,197	$1,459	$1,669	$2,384	$1,376	$1,399	$1,571	$1,478	$1,509

Table 26: Total HVAC Savings Relative to Base (excludes lighting, plug/equipment loads, and domestic hot water)

	ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
ASHRAE 90.1 Climate Zone	2A	3A	3B	3C	4C	5	5A	5B	6A
Model:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	-	-	-	-	-	-	-	-	-
2	$4	$8	$14	$30	$7	$6	$5	$12	$6
3	$4	$4	$12	$17	$8	$3	$4	-	$4
4	$6	$9	$23	$40	$12	$6	$7	$7	$8
5	$7	$4	$22	$31	$17	$4	$7	-$2	$8
6	$9	$8	$28	$44	$19	$7	$8	$3	$11
7	$1	$5	$2	$8	$12	$8	$4	$6	$9
8	$4	$10	$11	$30	$16	$12	$6	$14	$16
9	$2	$7	$2	$16	$25	$15	$6	$11	$26
10	$4	$9	$8	$29	$27	$18	$8	$16	$29
11	$2	$3	$7	$13	$10	$4	$4	$2	$6
12	$5	$8	$17	$35	$14	$9	$6	$10	$13
13	$5	$8	$13	$24	$20	$9	$7	$4	$13
14	$6	$9	$20	$37	$22	$12	$9	$9	$18

Table 27: Annual kWh Savings by City

	ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
ASHRAE 90.1 Climate Zone	2A	3A	3B	3C	4C	5	5A	5B	6A
Model:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	0	0	0	0	0	0	0	0	0
2	44	69	77	83	48	51	54	78	57
3	70	62	84	57	39	30	34	35	42
4	102	111	140	119	73	66	72	90	82
5	143	121	163	110	77	60	67	67	83
6	163	150	197	147	96	81	89	100	107
7	8	19	1	5	9	7	10	-3	16
8	41	68	55	64	43	44	49	53	57
9	17	36	-5	4	15	13	18	-9	32
10	35	65	27	39	35	34	41	24	55
11	43	41	46	34	25	20	23	17	30
12	74	91	101	94	59	56	62	74	70
13	83	82	86	61	47	38	44	32	59
14	103	111	118	97	67	59	67	64	82

Table 28: Annual Natural Gas Savings by City (therms)

	ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
ASHRAE 90.1 Climate Zone	2A	3A	3B	3C	4C	5	5A	5B	6A
Model:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	-	-	-	-	-	-	-	-	-
2	1	2	1	2	1	2	1	3	3
3	-1	-5	-3	-2	4	-1	3	-8	2
4	-1	-3	-2	-1	5	1	4	-5	4
5	-3	-10	-7	-6	8	-1	8	-16	4
6	-3	-9	-6	-5	9	0	8	-14	5
7	1	1	2	7	10	10	12	8	13
8	1	3	3	8	11	11	13	11	15
9	1	3	4	15	22	21	25	18	27
10	1	4	5	16	23	22	25	20	29
11	-1	-2	-1	2	6	4	7	-1	6
12	0	-1	0	3	7	5	8	2	8
13	-1	-4	-1	4	14	9	15	0	15
14	-1	-3	-1	5	15	10	16	2	16

Table 29: Total kBtu Savings by City (1 therm = 100 kBtu, 1 kWh = 3.412 kBtu)

	ORLANDO	DALLAS	LOS ANGELES (CA-CZ9)	NAPA (CA-CZ2)	SEATTLE	BOSTON	CHICACO	DENVER	MINNEAPOLIS
ASHRAE 90.1 Climate Zone	2A	3A	3B	3C	4C	5	5A	5B	6A
Model:	Hot-Humid	Warm-Humid	Warm-Dry	Warm-Marine	Mixed-Marine	Cool	Cool-Humid	Cool-Dry	Cold-Humid
1 (base)	-	-	-	-	-	-	-	-	-
2	250	435	363	483	264	374	284	566	494
3	139	-288	-13	-6	533	2	416	-681	343
4	248	79	278	306	749	325	646	-193	680
5	188	-587	-144	-225	1,063	105	1,029	-1,371	683
6	256	-388	72	2	1,228	276	1,104	-1,059	865
7	127	165	203	717	1,031	1,024	1,234	790	1,355
8	240	532	488	1,018	1,247	1,250	1,467	1,281	1,694
9	158	423	383	1,514	2,251	2,144	2,561	1,769	2,809
10	219	622	592	1,733	2,419	2,316	2,640	2,082	3,088
11	47	-60	57	316	685	468	778	-42	702
12	252	210	345	621	901	691	1,012	452	1,039
13	183	-120	193	608	1,560	1,030	1,650	109	1,701
14	251	79	303	831	1,729	1,201	1,829	418	1,880

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