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Climate-Specific Passive Building Standards

Building America Report - 1405

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Abstract:

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

Climate-Specific Passive Building Standards

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Betsy Pettit (Building Science Corporation)

October 2014

Building AMERICA
U.S. Department of Energy

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Task 11: Additional Research Activities

Task 11.3.2: Validation of Climate Specific Passive Building Standards as Basis for Next Generation Zero Energy Ready Home

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Definitions

ACH50	Air changes per hour at 50 Pascals pressure difference
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America
BSC	Building Science Corporation
CBECS	Commercial Buildings Energy Consumption Survey
CDD65	Cooling Degree Days, base 65° F
CFA	Conditioned Floor Area
CFL	Compact Fluorescent Light
CO2	Carbon Dioxide
DC	District of Columbia
DOE	Department of Energy (United States of America)
EPS	Expanded Polystyrene
ERV	Energy Recovery Ventilator
HDD65	Heating Degree Days, base 65° F
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilator
HSPF	Heating Season Performance Factor
iCFA	Conditioned floor area by interior dimensions
IEA	International Energy Agency
IECC	International Energy Conservation Code
ISO	International Organization for Standards
NREL	National Renewable Energy Laboratory
OC	On-center spacing distance
OSB	Oriented Strand Board
PHI	Passivhaus Institute (Darmstadt, Germany)

PHIUS	Passive House Institute US
PHPP	Passive House Planning Package
PV	Photovoltaic
RECS	Residential Energy Consumption Survey
RESNET	Residential Energy Services Network
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SSCD	Specific space cooling demand
SSHD	Specific space heat demand
TC	Technical Committee
TFA	Treated floor area
WUFI	Wärme und Feuchteinstationär (Heat and Moisture, Transient)
XPS	Extruded Polystyrene
ZNE	Zero Net Energy

Executive Summary

Of the various measures that can drive building performance towards net zero, passive measures are the most preferable. They result in durable construction, increased comfort, health, and resiliency, and are the most cost-effective, up to a point. In the larger picture, conservation plays a critical role in scenarios trying to shift the current energy economy towards a sustainable energy economy. Stringent conservation guidelines are necessary in addition to the aggressive build out of renewable energies so that the targets can be met.

The reported work is an up to date, independent study of how much investment in passive measures can be economically justified as cost-*competitive*, if not strictly cost-optimal. PHIUS, BSC's industry partner in the study, has been certifying buildings to a set of European-derived passive energy performance standards that put residential buildings at a rough economic optimum. However, it stands to reason that the optimum levels of envelope investment would be not only cost-specific (fuel costs and measure costs) but also climate-dependent. The Building America program has a long history of supporting efforts to identify optimum levels of investment in passive measures, active measures, and on-site photovoltaic energy production. DOE funded NREL to develop the BEopt software for building energy optimization to help identify the optimum level of investment in efficiency before PV becomes more cost-effective. As a very general matter, PHIUS takes a "best of both worlds" attitude to issues where European and North American approaches differ.

A fundamental property of climates is that the correlation is weak between degree-days (which influence annual energy demand) and design temperatures (which influence peak loads). Low peak loads are associated with passive building benefits, but it is the annual energy savings that must pay back the investment in upgrades to reduce peak loads. In particular, the relationship between degree-days and design temperatures differs between Central Europe and much of North America.

PHIUS+ certification that uses European energy metrics and specific standards as written has resulted in (broadly speaking) passive-solar-esque designs with a tendency to overheating, and discouragingly high cost premiums. Adjustments to the criteria are necessary to redeem the promises of the passive building standard for North America.

The central question studied is where to set performance standards on annual demands and peak loads, in order to deliver the most passive building benefits, in an economically feasible, climate-by-climate basis.

In late 2011, a volunteer Technical Committee (TC) was formed at PHIUS, and was tasked to work on standard adaptation, among other things. The involvement of the committee set the frame for the work reported here.

1 Framing the issue

Passive building design and construction dates back to ancient times. We owe the reawakening to it in our culture to the North American builders responding to the energy crisis of the 1970s. PHIUS acknowledges that passive house was born in Canada and the U.S. in name and concept. With the waning of the energy crisis it was mostly forgotten about for a generation (about 1982-2002).

Meanwhile, the Passivhaus Institut picked it up and made a lot of progress on it in Germany. They devised a pass/fail performance standard, developed software to support the required modeling calculations, published their standard and encouraged people to use and apply it, and trained certifiers.

People did use that standard, but in setting up their programs, usually tweaked something. The Austrians had a weak verification regime (self-certification) and got great market share. The equivalent Swiss standard Minergie-P effectively increased (loosened) the heating demand limit by changing the reference floor area. The Swedes opted for a peak-load-only criterion of 15-17 W/m^2 (4.76-5.39 $Btu/hr{\cdot}ft^2$) instead of 10 W/m^2 (3.17 $Btu/hr{\cdot}ft^2$), with an additional allowance for small structures [Jacobson 2013]. Brussels tightened the primary (source) energy criterion, but allowed PV generation to offset it [Dockx, 2013]. Therefore, it is fitting that adaptations be made to the North American climates, costs, and cultural context.

From its inception and to this writing, PHIUS has hewed closely to PHI's published standard, if anything strengthening its rigor as to field quality assurance. PHIUS has been in the certification business, certifying to an existing standard. PHIUS is moving into the standard-setting business, in order to make necessary and appropriate adjustments.

By 2008 it was evident that there were significant issues with applying the European derived energy metric in the US. For one thing, it was clear that "tunneling through the cost barrier" wouldn't work out as well in the U.S. as in Germany. The general idea of taking cost out of the mechanical system and putting it into the envelope is valid, but there wasn't as much savings to be had. For another thing, the winter design temperatures don't moderate very quickly going south, making it very hard to justify a design for low peak load (more about this in 4.1 below). Nevertheless, PHIUS finds great merit in the concept of a pass/fail performance standard as a way of building to top-level high performance, resilience, health and comfort.

This work is motivated in particular by the need to resolve the issues that arose, as well as in part by a positive vision to broaden passive house. In a number of ways, PHI's standard was attuned to their climate and culture; their initial work was simplified by focusing on where they were. Also, it turned out that some of the old-time North American passive house builders and super-insulators were still around. "This is not new," they said. PHIUS' demonstration projects from the beginning emphasized affordability and the use of domestic materials and components. North America is a large and technically advanced place; a considerable building-science and high-performance building community exists and has useful and relevant resources.

In 2012, the U.S. Department of Energy (DOE) recognized passive building standards as an excellent path toward the goal of zero- and positive-energy buildings. DOE entered into a partnership with Passive House Institute US (PHIUS) to co-promote these goals. As part of the agreement, PHIUS+ Certification that includes passive building design verification as well as RESNET-approved quality assurance protocols, was re-aligned to also yield DOE Challenge Home status (now Zero Energy Ready Home).

This effort – connecting PHIUS+ certification with DOE Zero Energy Ready Home – as it stands - has dramatically driven the demand for top level high-performance homes in the mass market.

Under the leadership of PHIUS, passive building has grown dramatically in the U.S. market over the past few years (Figure). The number of PHIUS+ project certifications is growing exponentially [PHIUS].

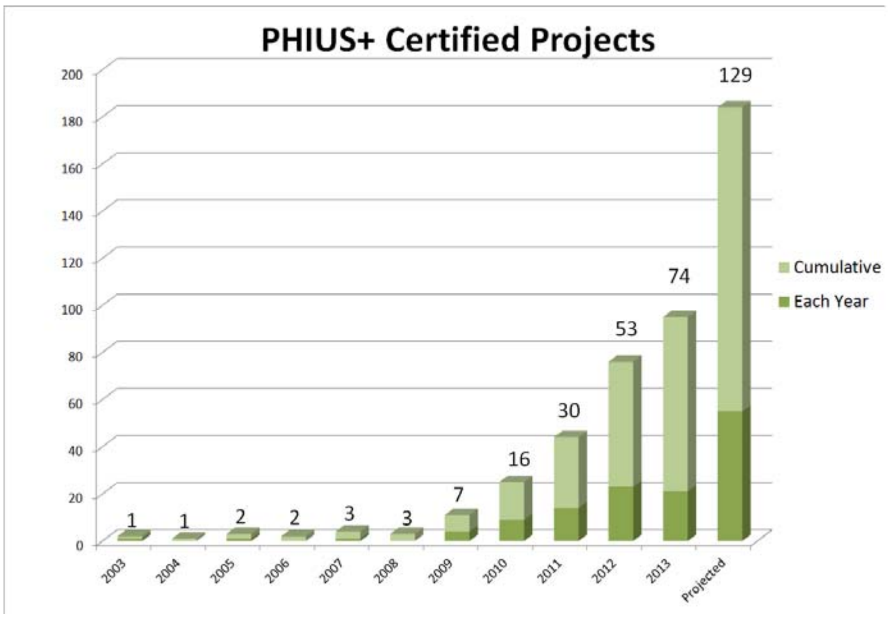


Figure 1. PHIUS+ certified passive projects trend of the past 10 years.

A refined climate-specific passive building standard could form the basis for the next generation Zero Energy Ready Home, if those metrics and design guidelines can be refined and verified to exceed the Building America home cost and performance targets.

Given the large proportion of energy used in buildings (33-44% of society's total), leaders in the building industry have challenged professionals and government officials to strive toward more stringent energy standards for buildings. Prominent examples are the 2030 Challenge by architect Ed Mazria, and the US DOE Zero Energy Ready Home program itself. The 2030 Challenge calls for buildings to be net zero by 2030. The Challenge Home program was recently renamed Zero Energy Ready, reflecting the same goal without requiring net zero performance at construction. Instead, Zero Energy Ready assures the inclusion of high-performance envelope measures, while allowing for the simple addition of renewables in the future.

2 Things to change, things to keep the same

With due respect to all that came before, and other current efforts, PHI's standard is the baseline starting point. PHIUS' critique of it is intended to be rational and cognizant of its principles.

2.1 Things to keep the same

The proposed adapted standard is still performance-based, that is, based mostly on modeled performance, as opposed to a prescriptive approach or an outcome-based approach.

It is still pass/fail.

The same criteria apply to all types and sizes of buildings (except that for commercial buildings a case-by-case allowance would be made for process loads.) In the future it might be necessary to ramify commercial specific standards, but for now it keeps things simpler and more importantly, it does the right thing in terms of design incentive: The studies are predicated on providing housing that is typical for the North America market (i.e. the three-bedroom house). More efficient forms of housing, such as multifamily units, will have an easier time meeting the criteria, while less efficient forms, such as detached "tiny houses" will have a harder time of it.

Still three pillars

Finally, the standard still has the same three pillars: limits on the space conditioning loads, a limit on the total source energy, and an air-tightness requirement. This high-level organization, with its three marquee-level criteria, has an intellectual appeal, and makes it easy to remember and succinctly describe the standard.

The space conditioning criteria limit the energy use "downstream" of the heating and cooling equipment (as opposed to the site energy supplied to the equipment). Therefore, those criteria must be met with "passive" measures alone.

The view of what constitutes a passive measure remains the same – it includes fan- and pump-assisted devices such as HRVs, earth air tubes, brine loops, and whole-house fans, in addition to insulation, air-sealing, overhangs and such. See Appendix F for an inclusive list.

The second pillar is the limit on total source energy – space conditioning energy plus all the other things energy is used for in the building, such as lights and hot water.

The third pillar is the mandatory level of air-tightness.

2.2 Things to change – three pillars reconsidered

The TC has reconsidered all three pillars. Each of these studies was compartmentalized according to the *appropriate underlying principle*:

The space conditioning criteria come from considering the economic, cost-competitive levels of investment in passive measures.

The source energy limit comes from considering the global impact of energy used in building operation (namely carbon dioxide and nuclear waste.)

The air-tightness requirement comes from consideration of building durability and mold risk. The air-leakage study is beyond the scope of this report, which is focused on the space conditioning. The matter of source energy will be discussed later in the report. But first some other changes need to be noted.

2.3 Other notable changes

- The Technical Committee agreed on a simplified reference floor area definition (iCFA): Floor area measured on the interior dimensions of the passive house thermal envelope, drywall-to-drywall, where ceiling height is greater than or equal to seven feet. This specifically includes stairs and interior partitions, as well as baseboards and cabinets. It specifically excludes open-to-below.

- It must be noted that the efficiency ratings of heat recovery ventilators aren't apples-to-apples comparable between PHI and domestic institutes (HVI and AHRI.) Up to now PHIUS has been using a rule of thumb from PHI, "subtract 12% from the sensible efficiency of non-PHI-rated units." The TC recently determined more nuanced adjustments to HVI and AHRI ratings that bring them closer to comparability with PHI rating, and the 12% deduction remains only for units that don't have any third party rating. This work is also beyond the scope of this report and is being written up separately.

- Though more a business matter than a technical matter, the TC supports the idea of offering two additional certifications (as add-ons, not alternates). One is for source-net-zero, and the other is for a traditional low energy building with a 1 Watt/ft2 or 10 W/m2 peak heat load.

Though the bulk of the work for this report concerns space conditioning, the source energy pillar needed to be addressed first because the question of lighting and miscellaneous electric loads is a critical-path *both* for source energy, *and* for internal gains which affect space conditioning.

3 Source energy

Having a criterion on source energy is appropriate, as it aligns with the goals of BA and NREL. Source energy serves well as a proxy for the global environmental impact of CO_2 emissions from fossil fuels. In the context of building design, a source energy criterion incents efficient equipment, not just for heating and cooling but for all other purposes as well.

Motivation for the source energy limit comes from the Intergovernmental Panel on Climate Change (IPCC), which estimates that in order to have a 66% chance of less than a 2 °C global temperature rise, all-time total emissions should stay below 800 Gigatons CO_2 equivalent. There is some uncertainty in how much has been emitted so far. [IPCC 2013]

The atmosphere can be regarded as the ultimate commons; CO_2 emissions blow around the world and affect everyone. A fair-share allocation of the remaining emission budget to each living person, assuming a linear glide path to zero emissions in 2050, gives a range of 2.2 to 3.8 tons per person per year for all purposes. By way of contrast, IEA data shows the US running at about 17 tons per person and year for all purposes. (See Table 1.)

Table 1. CO_2 fair share numbers.

Tons/person/year	Today	2050
USA emissions, all purposes, Randers (2.8 C by 2050)	18	9.4
IEA 2-degree-C scenario, USA	17	3.8
Building sector (assuming 28-33% of total) Randers	5.5	2.9
IEA, building sector, if all savings from new construction	5.2	3.2
Fair share of remainder of IPCC budget 800Gt, high estimate, linear glide to zero in 2050, no budget for the unborn.	3.8	0
Ditto, low estimate	2.2	0
Building sector share, hi	1.1	0
Building sector share, lo	0.7	0
Equivalent of 120 kWh/m2 source energy limit	1.0	

Giving the building sector its typical 28-33% share of the total 2.2-to-3.8,ton/person/year leaves 0.7-to-1.1 for the building sector. That is approximately where the current limit is in PHI's standard, i.e. 120 kWh/m2/year converts to 1 ton/person/year at a standard occupancy of 35 m2/person. Bottom line, there is no great justification for any relaxation of the current source energy criterion.

This source energy standard is aggressive from the IEA's point of view. Their 2°C scenarios are not counting on much reduction from the building sector in the developed world due to low turnover of the building stock. For the US, they picture the main opportunity as de-carbonization of the electric grid by large-scale deployment of renewables.

The perspective on source energy taken here is somewhat different than the one for which BEopt is braced. BEopt's implied perspective is that source energy is what matters, and economic analysis determines the level of investment in conservation measures (be they active or passive) versus PV.

The passive-building perspective is that space-conditioning energy and investment in passive measures are subject to economics, but total source energy is *not*, it is subject to a *cap*, based on fair-share-of-the-atmosphere considerations.

The Technical Committee agreed on the following changes relating to source energy calculation:

- Changing the source energy factor for grid electricity mix from 2.7 to 3.1.

The US electric grid is known to have source energy factors ranging from 2.374 to 3.549 depending on the major interconnect region, with a national average of 3.138. [NREL TP-550-38617, table B-2]. For the sake of simplicity and a level playing field, it is reasonable to use the national average. In recognition that the grid has probably gotten cleaner since the report was published, one can round down.

- For residential projects it is appropriate to change to a per-person budget, based on a fair-share of the atmosphere consideration. Occupancy is therefore taken to be the number of bedrooms plus one, per dwelling unit.

The limit for non-residential projects such as schools and offices would stay at 120 kWh/m2.yr (38.1 kBtu/ft2.yr). Additional allowance for process loads in commercial buildings can be determined on a case-by-case basis.

- For residential projects, the defaults for lighting and plug loads increase to 80% of RESNET levels.

Specifically, this refers to clause 303.4.1.7, sub-clauses .1, .2.2, .2.3, and .2.4 of the Mortgage Industry National Home Energy Rating Systems Standards, Jan. 1, 2013. An example is shown in Figure 2 below. For purposes of this calculation, the conditioned floor area (CFA) is the exterior-dimension floor area of the conditioned spaces, per RESNET rules. These are about six times the PHPP defaults but lower than Building America baseline home.

RESNET defaults for energy use by “televisions and miscellaneous electric loads” are substantially higher than the current equivalent baseline defaults for “consumer electronics and small appliances” in PHPP and WUFI Passive. The same goes for lighting, and Building America formulas would give higher numbers yet. The formulas work a bit differently – the baseline formulas are strictly per person, whereas RESNET uses a combination of per-person and per-square foot terms (conditioned floor area, exterior dimensions).

The low PHPP defaults are grossly unrealistic, a discrepancy that must be fixed. Two related objections have been raised:

Objection 1: “But *shouldn’t* we be using less?”

Answer: Yes, but assuming that it’s low has no power over occupants. The effect is actually reversed because it fools the designer into thinking they have more latitude on source energy.

		Mortgage Industry National Home Energy Rating Systems Standards, Jan. 1, 2013	80%
CFA (conditioned floor area)	2080	Clause:	
Number of bedrooms	3		
Televisions + Misc. Elect. Loads (kWh/yr)	2,513	303.4.1.7.1	2,010
% of high efficacy lighting in qualifying interior fixtures	100%		
Interior lighting (kWh/yr)	882	303.4.1.7.2.2	706
% of high efficacy lighting in qualifying exterior fixtures	100%		
Exterior Lighting (kWh/yr)	51	303.4.1.7.2.3	41
% of high efficacy lighting in qualifying garage fixtures	100%		
Garage Lighting (if garage is present) (kWh/yr)	25	303.4.1.7.2.4	20
Lighting total	958		

Figure 2. Lighting and plug loads example calculation, standard-adaptation study building.

Objection 2: “Don’t the resulting higher internal heat gains weaken the incentive to invest in the shell to reduce heat demand? Think of the low-energy future long term.”

Answer: Yes, in heating-dominated climates. But it’s important to have credibility as to the current reality and to use assumptions that are as accurate as possible. Using unrealistic assumptions to game annual demands up and/or peak loads down would weaken the program.

PHIUS certification staff experimented with allowing detailed lighting and plug load itemization for residential, but advises that be discontinued – it’s difficult to verify and allows too much possible gaming of the system on a case by case basis. (For nonresidential buildings, lighting and miscellaneous loads are more plausibly under the designers’ control.)

- Such an increase in residential lighting and plug load defaults is a large change that makes it considerably harder to meet the source energy target. Straightforward conversion of the 120 kWh/m2.year limit times 35 m2/person standard occupancy would give a limit of 4200 kWh/person.yr. A review of previously certified projects showed a median source energy design for 4100 kWh/person.yr, but with lighting and plug load defaults adjusted to RESNET levels, the median would have been almost 6600 kWh/person.yr. Therefore, as a shock absorber, the source energy limit should be temporarily relieved to 6000 kWh/person.yr, returning to 4200 by a date to be determined.

- Also, currently, the only renewable energy that "counts" towards reducing source energy is solar thermal. The Committee agreed to put other renewable generation on the same footing if it is used as it is produced. Therefore, an estimate of coincident production-and-use of energy from renewable energy systems (such as PV) may be included in the calculation similarly to the way solar thermal systems are currently treated, that is, the limit would apply to source energy consumption net of that generation. Dynamic simulations with hourly time resolution are probably good enough for now. For PV specifically, an example utilization curve is shown in Figure 3.

3.1 Occupant behavior roundup

In the space conditioning studies discussed below, as in regular project planning, occupant behavior is standardized. The compromise assumptions represent a partial upgrade of the occupants, as follows. Assume people can:

- Tolerate 68 F winter, 77 summer.
- Operate windows for natural ventilation cooling.
- Put up solar screens seasonally.
- Use lighting and plug loads at levels that equal 80% of RESNET (less than BA).
- Use hot water as per BA assumptions (~50% higher than PHPP).
- Have exhaust range hoods and dryers per BA assumptions.

PV/Total	Live utilization
0	1
0.09	1
0.19	0.96
0.38	0.74
0.95	0.39
1.5	0.27

Chicago climate
Array S facing at latitude tilt

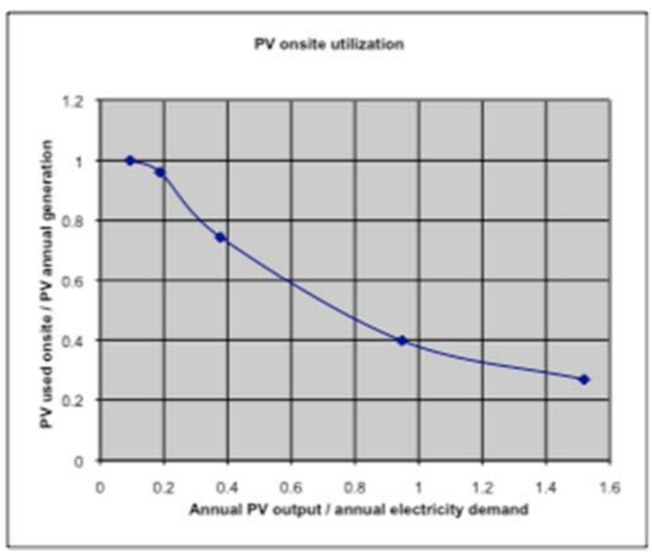


Figure 3. Example estimate of coincident production-and-use of PV electricity.

4 Space conditioning

The question addressed in the space conditioning study is basically, “how much can we reasonably invest in passive measures?”.

PHI claims that the “economic optimum” occurs at 10 W/m2 peak heat load or the 4.75 kBtu/ft2.yr annual heat demand everywhere in the world [PHI, Greenbuild 2013]. “That can’t be right” is the objection. In fact, applying this standard in the varying North American climates oftentimes drives costs far beyond the economic optimum. NREL’s BEopt program provides a tool to study optimization by climate.

Early on, it became clear that cost is a moving target. While that is true, it can be dealt with by revising the standard every three to five years, much like the building code cycle.

4.1 Passive house historical background

It might be said that concern with space conditioning is a signature, differentiating feature of the passive house concept. The particular form or expression that concern takes in a codified standard is thus central to its meaning.

The concept of passive house is rooted in North America and was developed under funding from US and Canadian governments as a response to the energy crisis in 1973.

Two converging paths of lessons learned the “hard way” led William Shurcliff to a “package of measures” for cold climates, and a performance target of an 85% reduction in furnace size (equivalent to a peak load criterion) [Shurcliff 1986].

The first path might be called the superinsulation or building science route. It was found that superinsulation did not work well without air-sealing and good detailing, that air-sealing did not work well without ventilation, and that ventilation did not work well (regarding distribution and operation of combustion appliances) unless it was balanced.

The second path might be called the passive solar or architect’s route. A 2005 article by Dan Chiras listed a number of downsides of the classic “mass-and-glass” approach (large south-facing glazing for solar gain, and thermal mass for storage). Fixing these problems entailed using more insulation and air-sealing, and less mass and glass [Chiras 2005].

Shurcliff considered the concept development complete by 1986, and referred to it early as passive house [Shurcliff 1982] and later as superinsulation. At that point, he was simply awaiting better components: high performance windows, highly efficient heat recovery ventilators, minimized compact space conditioning units, and a new generation of vapor retarders [Shurcliff 1988].

A review of the history of superinsulation was presented by Martin Holladay at the 14th Annual Westford Symposium on Building Science [Holladay 2010]. Wolfgang Feist, the director of the German Passivhaus Institute, has acknowledged the inspiration of the work of William Shurcliff and Harold Orr, both significant contributors to early research and publications in the United States and Canada.

At the 2012 North American Passive House Conference, Joseph Lstiburek presented a review of lessons learned from 20 projects in Canada's R-2000 program in the 1970s [Lstiburek 2012].

The basic concept of a low energy building that does not need a conventional heating system was written into the predecessor of the *International Energy Conservation Code* as a high-level alternate path already back in 1975, and has been kept to this day (see IECC §C101.5.2 Low energy buildings). [ICC 2012] The language implies, at 1 W/sf heat load the building doesn't need a heating system and can live off internal gains. It is vague as to the conditions. It could be interpreted that the heat load *net* of internal gains is actually *zero,* that is even more extreme than PHI's definition.

The definition of a passivhaus espoused by PHI is essentially, "supply air heating sufficient," which is quantified as a peak heating/cooling load of no more than 10 W/m^2 (3.17 $Btu/h{\cdot}ft^2$).

"A Passivhaus is a building for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air." [Passipedia.org, 2014].

But then, PHI introduced an alternate, proxy criterion on *Annual* heat demand, 15 kWh/m2.yr (4.75 kBtu/ft2.yr. The alternate criterion was introduced for good reason: annual demand can be calculated more accurately than peak load – especially if one wishes to develop a static calculation tool to give planners faster feedback. Buildings could be certified on either the peak or the annual criterion.

In 2007, PHIUS started promoting and applying this, just as written, in all climates of the US and Canada. A couple of issues came to light.

> In the climate of central Europe, the relationship between the annual demand and peak load was such that a building that achieves 15 $kWh/m^2{\cdot}yr$ (4.75 $kBtu/ft^2{\cdot}yr$) annual heat demand would by-and-large meet the peak load definition as well. Furthermore it was found / claimed that the level of envelope investment needed to achieve this performance was cost-competitive, even roughly cost-*optimal* – marking the point where one could "tunnel through the cost barrier" to higher performance. "Tunneling through the cost barrier" implies saving substantial costs on the mechanical and heat distribution systems, and shifting those savings to the envelope/enclosure. This cost-optimality has been a key selling point for the concept in Europe.
>
> In North America, "tunneling through the cost barrier" was not achieved. Unlike Germany, there is not such a clear breakpoint where an expensive baseline boiler and hydronic distribution system (the typical heating system in Europe) can be eliminated for great savings. Also, presently there is not much cost savings on specialty small-capacity heating and cooling devices, relative to high-capacity commodity equipment. That might be a temporary problem, but it doesn't seem likely to change quickly – it appears that most of the market for furnaces and air conditioners is replacements going into old high-demand buildings. It is critical to acknowledge the reality of the different cost picture in North America.

Another problem that came to light is that the relation between degree-days and peak design temperature varies by climate; they are but weakly correlated. Away from the coasts, peak design conditions are relatively harsh compared to degree-days. As a consequence the alternate, annual heat demand criterion was almost always easier and therefore almost always used. Because the solar resource is generally greater in the US than Germany, annual demand could be pushed down with solar gains, leading to over-glazed, passive-solar-esque designs.

North American and European Climate Comparisons

In much of North America, peak heating load conditions are harsher relative to annual demand than in Europe. This is an unfortunate reality, because while the design for low peak load delivers the comfort and passive-survivability benefits, it is the annual energy savings that must *pay back* that investment. Therefore, where the annual demand is low relative to the peak, or the peak is harsh relative to the annual, the economics of a design for low peak load (i.e., “supply air heating sufficient”) will be even more challenging.

Tables 1 through 5 show some examples of these patterns. PHI literature usually quotes -10°C/14°F as a peak load design temperature for central Europe; that turns out to correspond to the ASHRAE 99.6% design temperature for central Europe. The following is a comparison of climates on that basis (data taken from ASHRAE [2013]).

In North America on the East coast (Table 1), Boston (Climate Zone 5A) is similar to Frankfurt, Germany (Climate Zone 5) for annual demand, as indicated by heating degree days (highlighted in red), but has a harsher peak load condition. One needs to go south to Baltimore or New York (Climate Zone 4A), to find peak conditions comparable to Germany (highlighted in blue).

Table 2: Design temperatures and degree days, North America, Coastal, East

Cities	ASHRAE 99.6% design temp (°F)	ASHRAE 99% design temp (°F)	HDD65	CDD65
Frankfurt (5)	14.5	19.1	5570	308
Boston, MA (5A)	8.0	13.0	5596	750
Baltimore, MD (4A)	14.0	17.9	4552	1261
New York, NY (4A)	13.8	17.8	4843	984

On the Northwest coast/Pacific Northwest, the peak-versus-annual relation is closest to Europe (Table 2). The peak is actually milder at comparable annual demand. Seattle and Portland are actually milder on both peak and annual. One needs to go north almost to Prince Rupert for a peak load comparable to Frankfurt.

Table 3: North America, Pacific Northwest

Cities	ASHRAE 99.6% design temp (°F)	ASHRAE 99% design temp (°F)	HDD65	CDD65
Frankfurt (5)	14.5	19.1	5570	308
Squamish, BC (5)	18.3	22.4	5987	115
Portland, OR (4C)	25.2	29.5	4214	433
Prince Rupert, BC (6)	13.3	18.4	6993	1

In the mid-continental United States, places with similar heating degree-days to Germany have much harsher design temperatures. In the East and Midwest, one needs to go south almost to Nashville to find comparably mild peak conditions (Table 3). Annual demand there is substantially lower.

Table 4: US, mid-continent, East

Cities	ASHRAE 99.6% design temp (°F)	ASHRAE 99% design temp (°F)	HDD65	CDD65
Frankfurt (5)	14.5	19.1	5570	308
Pittsburgh, PA (5A)	5.2	9.9	5583	782
Indianapolis, IN (5A)	2.0	8.1	5272	1087
Decatur, IL (5A)	0.9	6.6	5442	1100
Louisville, KY (4A)	10.2	15.9	4109	1572
Nashville, TN (4A)	14.8	19.3	3518	1729

Out west the story is the same - places with similar heating degree-days to Germany have much harsher design temperatures – but the design conditions moderate more slowly going south. One has to go south almost to Lubbock for a comparably mild heating peak (Table 4). This far south, it is true that savings on cooling could also help the payback, but in cooling-*dominated* places there is a similar situation for a different reason: the passive measures like overhangs and thermal mass that are good for reducing peak cooling do not compete well with mechanical cooling when it comes to delivering annual savings.

Table 5: US, mid-continent, West-central

Cities	ASHRAE 99.6% design temp (°F)	ASHRAE 99% design temp (°F)	HDD65	CDD65
Frankfurt (5)	14.5	19.1	5570	308
Denver (5B)	0.5	6.6	5969	777
Kansas City (4A)	2.0	7.2	5012	1372
Amarillo (4B)	9.8	15.6	4102	1366
Lubbock (3B)	15.9	19.9	3275	1846

Back in the Midwest, going north of Indianapolis of course things get even harder. Madison, WI already has harsher peak conditions than Oslo, Norway (Table 5). Swedish passive house certifiers moderated their peak load criterion to 15 W/m^2 (4.76 Btu/h·ft^2) [Jacobson 2013].

Table 6: US, mid-continent, North

Cities	ASHRAE 99.6% design temp (°F)	ASHRAE 99% design temp (°F)	HDD65	CDD65
Frankfurt (5)	14.5	19.1	5570	308
Oslo, Norway (6)	-4.2	0.7	8855	40
Madison WI (6A)	-7.0	1.6	7104	620

The crux of the matter is that PHIUS+ certification tracking the European energy metrics and specific standards as written has tended to result (broadly speaking) in passive-solar-esque designs with a tendency to overheating, and discouragingly high cost premiums. The cost premiums would be even higher if one were to be "strict-constructionist" about meeting the supply-air-heating sufficient peak load definition / criterion.

By 2011 it became clear that the space-conditioning criteria needed some climate-dependent adjustment, if the standard was to deliver on the promise of deep energy savings cost-optimally (or at least cost-*competitively*.)

In a 2009 article, John Straube critiqued PHI's standard. While this article contained some misunderstandings, its basic point was accurate that in ASHRAE Climate Zones 5 through 7 in North America, the standard is not economically justifiable, by and large. This study is a response to that critique and other unpublished ones like it [Straube 2009].

Between 2008 and 2010, PHIUS followed PHI's definition of passive house: 10 W/m2 peak heat load – supply air heating sufficient, everywhere. Size the building assemblies to the heating system instead of the other way around. Everybody gets a hair dryer for space heat. Fair enough.

However, "everybody gets a hair dryer" is a *misapplication* of the fair share principle. That principle properly applies to the total source energy, not to space conditioning. The leveling principle for space conditioning is *economic competitiveness*. One can choose to define passive house as design for peak load 10 W/m2, or by an economic optimum, but not both, not everywhere at once.

In late 2011, a volunteer Technical Committee was formed at PHIUS, which was tasked to work on standard adaptation, among other things. The involvement of the committee set the frame for the work reported here.

4.2 Proposed framework for the space conditioning criteria

To ensure that enough energy is saved AND the benefits of low peak loads are preserved, a "both-and" set of criteria has been proposed. In other words, we propose to set limits on annual heat demand *and* peak heating load, as well as annual cooling demand *and* peak cooling load. So the criteria would read:

- Annual heating demand < A, and
- Annual cooling demand (sensible+latent) < B, and
- Peak heating load < C, and
- Peak cooling load < D.

These would vary by climate. The idea is to keep designs balanced and prevent any one aspect from getting out of hand.

In preliminary work, one proposal was to set criteria zone-by-zone for the ASHRAE/DOE climate zones. It is easy to see that this could lead to issues in borderline regions. Specifically: what if a project site is directly adjacent to a zone boundary? A continuous-function approach was deemed preferable.

5 Three phase test plan

5.1 Economic optimization studies

Here is an overview of the study process:

- A study building was moved around to ~100 locations, using BEopt to compute the series of optimal upgrade packages, from code minimum to max savings.
- The cost optimization was done under constraints, notably:
  - Forced air-tightness.
  - Forced window upgrades for 60 degrees F minimum interior surface temperature, climate-specific.
  - Partially upgraded occupants as noted in 3.1 above.
- A human judgment call was made, as to the point of deepest energy savings feasible, cost-competitively – location by location.
- The heating demand, cooling demand, peak heating load and peak cooling load at that point, were noted.
- Statistical models were fitted to the demands and peak loads so that target values can be generated for any location from site parameters like degree-days and design temperatures.

Phase 1 economic studies were conducted using BEopt version 2.2.0.1. As described by Christensen [2005], its basic purpose is to identify optimal building designs on the path to zero net energy. That optimal path appears as a U- or “swoosh”-shaped curve on a plot of annualized energy-related costs (mortgage + utilities) versus energy savings. The conceptual plot is shown in **Figure 4**.

At the left side, the reference building has high utility bills but no added finance cost for energy-saving or energy-generating upgrades. On the right side, the net zero upgraded building design has no energy bill, but a higher mortgage payment. Somewhere in between is a cost-optimal set of upgrades (point 2). At point 3, generating energy with PV becomes more cost-effective than conservation. As described by Christensen [2005]:

"The optimal path is defined as the lower bound of results from all possible building designs. … At each step along the path, BEopt runs individual simulations for all user-selected options and searches for the most cost-effective combination of options."

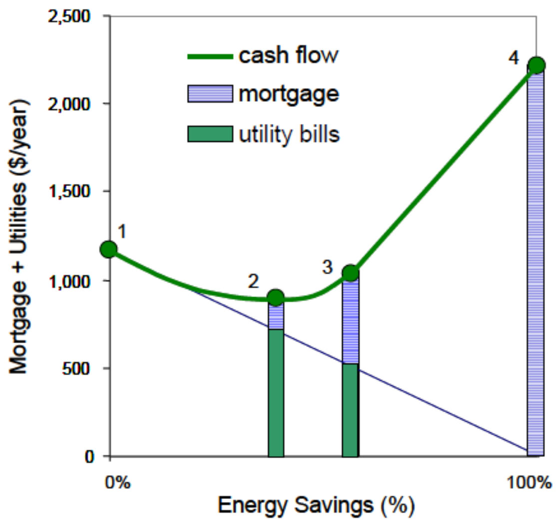


Figure 4: Conceptual plot of the path to ZNE

BEopt brings together a state-of-the-art dynamic simulation engine (EnergyPlus), a full-featured life cycle cost calculation module, an optimization algorithm, and a cost database. While the NREL construction cost database is not intended for project-specific analysis, it is by-and-large appropriate for relative comparison to a benchmark, with some cost overrides on a few key measures.

The basic procedure is to set up a model of a canonical / touchstone building of a fixed size and shape, then give the optimizer a number of "knobs" to turn (i.e., adding energy-saving measures), and then run an optimization. In optimization mode, BEopt determines a life-cycle-cost-optimal configuration for a series of progressively deeper energy savings (site or source), picking the lowest hanging fruit first, then the next lowest, and so on. The criteria for the standard are set by looking at the annual demands and peak loads in the study building for a point "near" the minimum cost, and setting the criteria at those levels for that climate. The exercise is then repeated for different climate locations.

The approach is similar to that of Kruger [2012]. The main difference from his work is that this study dispenses of the calibration to German cost (substituting North American expert judgment, that he implied would have been preferable anyway), constraining the optimizer differently, and keeping the heating and cooling demand separate when setting the criteria and also limiting peak loads.

In order to support interpolation or the fitting of continuous-function rules for the criteria, a judgement was made that at least 100 locations would be needed (a five-factor curve fit with ten two-way interactions and five quadratic terms has twenty adjustable parameters). Economic analyses were run on the 111 locations for which WUFI data is available (that supports dynamic simulations for comfort verification and hygrothermal checks). Figure 5 shows a map of these locations.

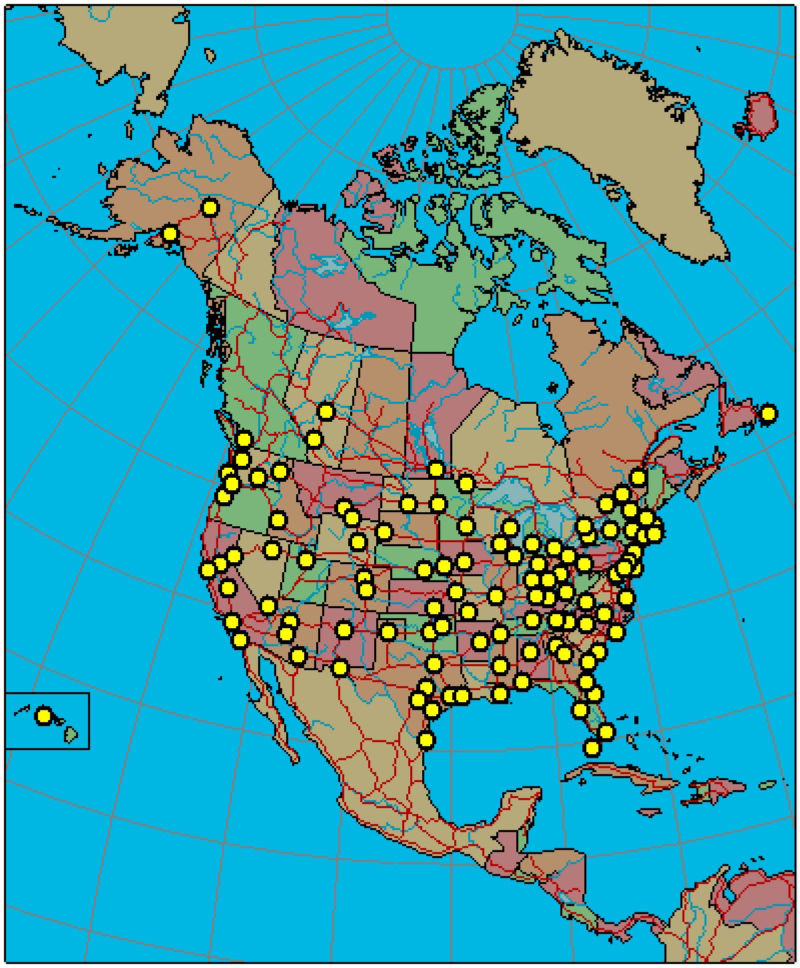


Figure 5: Climate locations for Phase 1 economic analysis

The study building and other constant factors

A single-family detached house was chosen for the studies, because it is the predominant housing type in the United States. The performance criteria are thereby predicated on providing housing in this very typical way. Projects using more efficient forms of housing (multifamily) will therefore have an easier job to meet the criteria, while less efficient forms (tiny houses) will have a harder time. This seems to us, fair enough for now. (Ramifying the study to different housing types could be a future project.)

Key parameters of the study building:

40 feet long by 26 wide by 19 high exterior dimensions, two stories, 3 bedroom, 2 bath.

- Finished floor area 2080 sf, notional TFA 1560 sf.
- Oriented short side south with neighbors at 20 feet east and west.
- Vented attic with cellulose insulation.
- Exterior-foam wall assembly.
- Slab-on-grade foundation.
- Window U-values constrained for comfort, location by location.
- Window area 15% of wall area (up to 40% concentration on South or North.)
- Air-tight, ducts inside.
- All-electric.

The Technical Committee also approved a number of other calculation protocol details, listed in Appendix A. It took some discussion to come to clarity about which parameters should be "knobs" for the optimizer, which should be reset to different values than the B10 benchmark and held fixed, and which should be left at benchmark values.

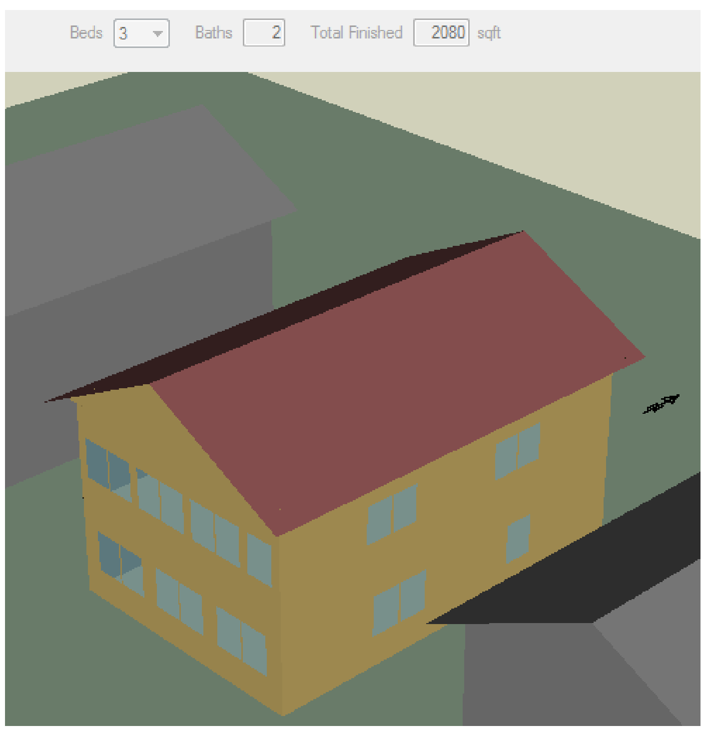


Figure 6: BEopt visualization of the study building

A report format was developed that, for each location, consists of three charts and a data table. Examples are shown below for the case of Chicago IL (along with a screenshot of the BEopt output window in Figure 7). On each chart, the optimal curve of annualized cost versus percentage energy savings (site) is plotted in green against the left axis. Indicator traces at the bottom blip up at the PV-start and solar-hot-water-start points.

The first chart also shows the incremental capital cost per gross square foot of floor area in red against the right axis (Figure 8). An alternate, "conservation-only" version of the optimal curve is also plotted in blue, which has the renewables contributions edited out of the sequence (the cost and energy savings increments at the PV-start and SHW-start steps are subtracted out of succeeding points[1]).

The second chart illustrates annual heating and cooling demands per square foot of notional treated floor area (Figure 9).

The third chart illustrates the heating and cooling peak loads or system capacities that BEopt determines according to ACCA Manual J calculation, again per square foot of TFA (Figure 10). The dark blue line shows the source energy per person in MWh/year.

The data table lists all of the graphed data, and also shows the option configuration for each optimal point, highlighting items that are different from the previous point (Table 7)

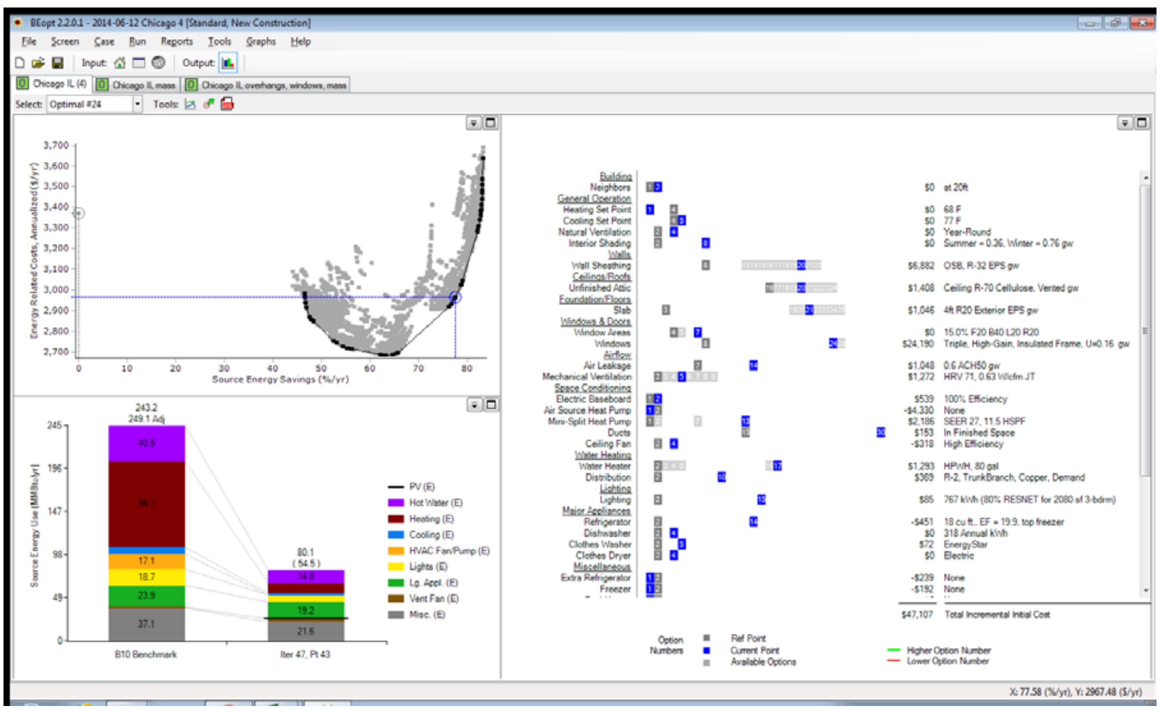


Figure 7: BEopt output screen, Chicago IL, at chosen cost-competitive point.

[1] This isn't a perfect adjustment – if another option changes at the same step as PV-start or SHW start, its cost and energy savings increment get subtracted out as well. This was not a common occurrence.

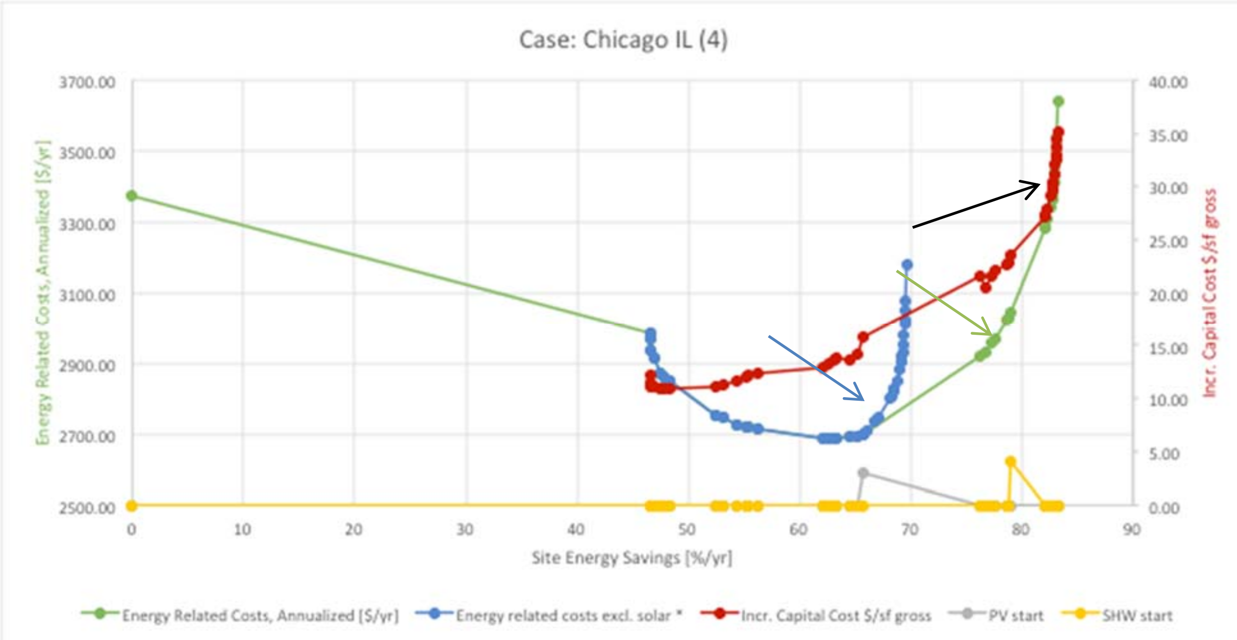


Figure 8: Economic analysis report example, Chicago IL, annualized costs & first-cost premium

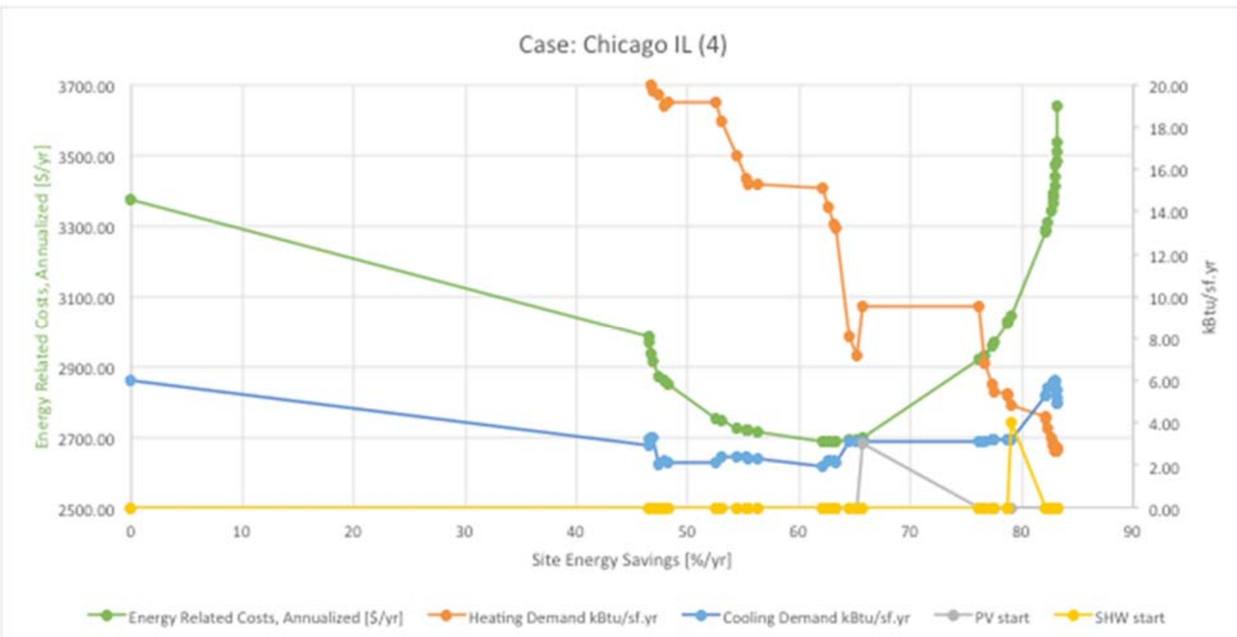


Figure 9: Economic analysis report example, Chicago IL, heating / cooling demand chart

A number to keep in mind for comparison here is the current certification limit of 4.75 kBtu/sf.yr. Compared to PHPP calculation, the MEL/Lighting and internal heat gain increase incorporated here causes about a 1.5-2.0 kBtu/sf.yr reduction in modeled annual heat demand and increase in cooling demand. That is, the same building “would have” modeled with higher annual heat demand under PHPP assumptions.

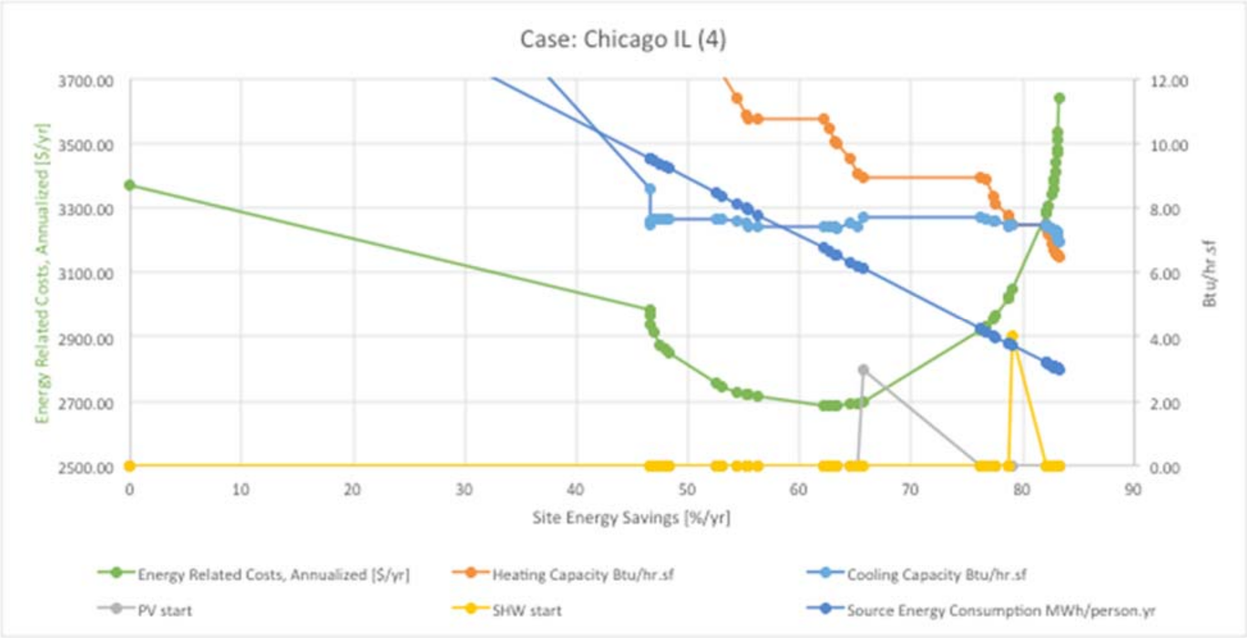


Figure 10: Economic analysis report example, Chicago IL, peak load chart (per Manual J)

The horizontal rules in Table 7 pick out some key points. Optimal point 14 was the minimum cost point. Optimal point 19 was the "PV start" point, where BEopt determined it makes more sense to add PV instead of more conservation.

Table 7: Economic analysis report, example table for Chicago IL

Case: Chicago IL (4)			Optimal #	detect	Point	Site Energy Savings [%/yr]	Energy Related Costs, Annualized [$/yr]	Incr. Capital Cost $/sf gross	Heating Demand kBtu/sf.yr	Cooling Demand kBtu/sf.yr	Heating Capacity Btu/hr.sf	Cooling Capacity Btu/hr.sf	Heat demand reduction	Cooling demand reduction	Heating capacity reduction	Cooling capacity reduction
					B10 Benchmark	0	3372.44		49.17	6.01	42.51	26.28				
1059	data!c1059	data!d1059	0		Start	46.55	2984.71	11.13	20.10	2.94	13.42	8.58	59%	51%	68%	67%
1060	data!c1060	data!d1060	1		Iter 14, Pt 18	46.6	2966.89	12.21	20.07	3.21	12.60	7.49	59%	46%	70%	72%
1061	data!c1061	data!d1061	2		Iter 14, Pt 19	46.68	2937.31	11.48	19.98	3.27	12.60	7.57	59%	46%	70%	71%
1072	data!c1072	data!d1072	13		Iter 26, Pt 28	62.08	2687.04	12.93	15.12	1.93	10.74	7.44	69%	68%	75%	72%
1073	data!c1073	data!d1073	14	Min cost	Iter 27, Pt 28	62.6	2684.90	13.25	14.23	2.18	10.47	7.44	71%	64%	75%	72%
1074	data!c1074	data!d1074	15		Iter 28, Pt 30	63.21	2685.06	13.69	13.44	2.18	10.08	7.40	73%	64%	76%	72%
1075	data!c1075	data!d1075	16		Iter 29, Pt 27	63.34	2685.19	13.79	13.25	2.13	9.97	7.34	73%	65%	77%	72%
1076	data!c1076	data!d1076	17		Iter 39, Pt 31	64.56	2690.07	13.66	8.07	3.14	9.56	7.53	84%	48%	78%	71%
1077	data!c1077	data!d1077	18		Iter 41, Pt 38	65.19	2693.37	14.21	7.21	3.14	9.06	7.42	85%	48%	79%	72%
1078	data!c1078	data!d1078	19	PV start	Iter 53, Pt 30	65.7	2697.59	15.82	9.52	3.14	8.96	7.69	81%	48%	79%	71%
1079	data!c1079	data!d1079	20		Iter 52, Pt 30	76.23	2920.46	21.50	9.52	3.14	8.96	7.69	81%	48%	79%	71%
1080	data!c1080	data!d1080	21		Iter 47, Pt 42	76.67	2932.85	20.51	6.79	3.14	8.88	7.65	86%	48%	79%	71%
1081	data!c1081	data!d1081	22		Iter 35, Pt 33	77.34	2957.68	21.65	5.85	3.20	8.33	7.60	88%	47%	80%	71%
1082	data!c1082	data!d1082	23		Iter 47, Pt 43	77.59	2967.48	22.10	5.51	3.20	8.13	7.58	89%	47%	81%	71%
1083	data!c1083	data!d1083	24		Iter 52, Pt 35	78.69	3022.22	22.70	5.40	3.20	7.77	7.49	89%	47%	82%	71%
1084	data!c1084	data!d1084	25		Iter 59, Pt 35	78.76	3027.53	22.90	5.28	3.20	7.69	7.44	89%	47%	82%	72%
1085	data!c1085	data!d1085	26	SHW start	Iter 59, Pt 45	79.03	3045.99	23.58	4.88	3.20	7.46	7.46	90%	47%	82%	72%
1086	data!c1086	data!d1086	27		Iter 61, Pt 14	82.09	3283.28	27.13	4.32	5.33	7.46	7.46	91%	11%	82%	72%

Wood Stud	Wall Sheathing	Exterior Finish	Unfinished Attic	Radiant Barrier	Slab
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-5 XPS	Vinyl, Light	Ceiling R-38 Cellulose, Vented	None	2ft R10 Perimeter, R5 Gap XPS
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-5 XPS	Vinyl, Light	Ceiling R-38 Cellulose, Vented	None	2ft R10 Perimeter, R5 Gap XPS
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-8 EPS gw	Vinyl, Light	Ceiling R-38 Cellulose, Vented	None	2ft R10 Perimeter, R5 Gap XPS
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-8 EPS gw	Vinyl, Light	Ceiling R-38 Cellulose, Vented	None	2ft R10 Perimeter, R5 Gap XPS
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-16 EPS gw	Vinyl, Light	Ceiling R-44 Cellulose, Vented	None	4ft R8 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-16 EPS gw	Vinyl, Light	Ceiling R-44 Cellulose, Vented	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-20 EPS gw	Vinyl, Light	Ceiling R-44 Cellulose, Vented	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-20 EPS gw	Vinyl, Light	Ceiling R-49 Cellulose, Vented	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-16 EPS gw	Vinyl, Light	Ceiling R-44 Cellulose, Vented	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-20 EPS gw	Vinyl, Light	Ceiling R-49 Cellulose, Vented	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-32 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-32 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-20 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-28 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-32 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-32 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-32 EPS gw	Vinyl, Light	Ceiling R-80 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-40 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw
R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	OSB, R-40 EPS gw	Vinyl, Light	Ceiling R-70 Cellulose, Vented gw	None	4ft R20 Exterior EPS gw

Nine cases were presented for TC preliminary review. Committee members raised concerns about the interaction between the space conditioning criteria and the source energy limit. That is, under the PHI protocol, the space conditioning criteria were usually the limiting factor, while the source energy target was relatively easy to meet. But with higher lighting and plug load defaults, and potentially higher space conditioning thresholds, the source energy limit could become the limiting factor.

If source energy ends up being harder to meet, then some additional measures would need to be taken, and the designer would be free to choose passive or active approaches. Therefore the calculation protocol was modified (and started over) to include “full-sized” options for the onsite renewables in BEopt that count against the source energy limit, i.e. solar hot water and PV. The PV array is limited to 2 kW; small enough that most of its output would be used live on-site and therefore count as reducing source energy (under the TC's prior resolution). In earlier rounds only a small 200 or 500 W system was used to “detect” the PV start point for comparison, and in the first round the optimizer was given passive knobs only. In the final round the optimizer had all 3 kinds of knobs - passive, equipment, and renewables. That gives a complete view of the economics and how passive measures fare in different climates.

Standard-setting heuristic

The PV start point would be a defensible level at which to set the criteria. But it may be appropriate to choose a more aggressive point on the cost-optimal curve, that is, one still cost-competitive but with less annual dollar savings.

There are a couple of motivations for pushing past the PV start point:

- One main motivation for doing so might be called the “non-energy benefits argument”. The higher-hanging measures are good for reducing the peak loads delivering high levels of thermal comfort and delivering more of the resilience benefits.

The rationale is that passive measures are better for the building owners and occupants than renewable generation alone. They increase the building’s resilience to utility outages, by minimizing heat losses and thus allowing interior temperature “coasting” during outages.

Therefore, passive building is a strategy not just for *mitigating against* climate change, but also for *adapting to* it (and the changes are already occurring.)

- There is a continuum, a tradeoff – the harder one pushes on the space conditioning criteria, the greater the "flavor" of passiveness, but the lower the cost-competitiveness. In any case, the source energy limit keeps the climate "safe" (~60% chance of 2°C warming or less).

Those of us with a "singular focus" on the peak loads might even wish for a version of BEopt that would optimize for them - peak load reductions on the X-axis - that is. But that method could end up sacrificing site energy savings for the sake of peak load reduction. Some TC members were adamant that the energy savings should take priority. BEopt does that, so could be used as is, but net energy savings is not the sole consideration. The TC as a whole was inclined to forgo some annual *dollar* savings if more peak load reductions could be realized. Consensus was reached on this point.

- The second kind of reason might be called the "more to life than money argument". While the TC decided that the economic analysis should be the driving factor and pointedly chose to assess it a conventional way with conventional assumptions about the future, the method has known blind spots and the assumptions might not turn out to be right:
  - A 30-year time horizon could be too short - most buildings last much longer,
  - Perhaps the discount rate should be zero (or lower),
  - Outage risk is not considered and should be, valuation of resilience benefits,
  - Inflation and fuel escalation rate statistics are inaccurate or will be different in the future,
  - Fuel price spikes accelerate payback quickly (what if shale is a bubble?)

Any/all of those thoughts could be a reason to push beyond the conventional economic optimum for more conservation and passive measures. One could argue that pushing past the cost optimum is actually a conservative approach given the uncertainty of above mentioned future developments and possible climate risks.

There is an opportunity for passive building design (or top level high-performance building design) to achieve a much greater total impact through wider adoption. The best results will be achieved in a "window of operation" between two limits. On one hand, aggressive performance standards can be set to deliver the benefits of passive building construction, but on the other hand, they should not be set so aggressively that they yield diminishing returns and long paybacks that discourage mainstream adoption. This project aimed to set standards that hit this "sweet spot."

The TC agreed upon the following heuristic for setting the criteria:

- Note the PV-start point.
- Note the knee of conservation-only cost curve and go a little past it, to where conservation is heading into diminishing returns. If that zone happens to straddle an upgrade from exhaust ventilation only to HRVs, prefer the point with the HRV (HRVs bring peak loads down and assure even distribution of fresh air).

Exception: if source energy is far over limit at PV start, pick PV start. (i.e. don't invest more in passive measures if challenged on source energy limit - save some money for onsite renewables, or novel measures).

Comparison to cost-parity with the benchmark turned out to be problematic for a couple of reasons. First, there were unintended consequences of changing to an all-electric building and state-by-state electricity prices. In places with expensive energy, everything was affordable in a sense: even measures that were deep into diminishing returns still showed cash flow. In places with cheap energy, distressingly little was affordable. It could be a problem that in these analyses, the energy prices are varying regionally but the construction costs are not, and they are probably somewhat correlated, which would tend to level things. Keying in on the diminishing returns behavior appeared to be a more robust procedure, not as sensitive to energy price variations.

Also, eliminating the statistical fractions of extra miscellaneous loads from the study house by itself gives something like a $400/yr cash flow boost, which is arguably "fake". That is, the annualized costs for the benchmark are over inflated, making it look like one could buy a lot of upgrades and still be ahead some $/year. This was particularly dramatic in the case of Alaska – the minisplit heat pump had a low COP and bought huge amounts of expensive electricity.

In the case of the Chicago example above, applying the above heuristic gravitated to optimal point 23 or 24 (highlighted in light orange). This straddles an upgrade from the 71% efficient HRV to the 88%.

In Figure 8, the blue arrow indicates where optimal point #23 is on the blue curve, and the green arrow indicates it on the green curve, as do the crosshairs in the upper left pane of Figure 7. The black arrow indicates about where a design for 4.75 kBtu/sf.yr annual heat demand would fall per PHPP calculation. (A 10 W/m2 peak load design by PHPP would be at or slightly above the last point at the top of the chart.)

Each location case was reviewed and a knee-of-the-curve point was picked. In many cases it was difficult to decide between two adjacent points where a large step occurred (such as an HRV upgrade, SHW start, or multiple upgrades in one step). In such cases both options were recorded.

Also, feedback was solicited from builders of high-performance homes, asking them what was the best they could practically do in their market and which study configuration most resembled it. Input from six locations was received and incorporated, and generally speaking confirmed that the heuristic was reasonable.

For purposes of summary, illustration, and comparison, the zone-by-zone median values that were picked for the space conditioning criteria according to the above heuristic are shown in Table 8 below. The corresponding values from picking the PV-start points are shown in Table 9.

Table 8: Zone median space conditioning targets, by diminishing returns heuristic

Zone	Specific space heating demand [kBtu/sf-iCFA.yr]	Specific space cooling demand [kBtu/sf-iCFA.yr]	Peak heating load (manual J) [Btu/sf-iCFA.hr]	Peak cooling load (manual J) [Btu/sf-iCFA.hr]	Recommended maximum window U (winter comfort) [Btu/h.sf.F]
8	13.2	0.2	8.4	5.0	0.10
7	7.5	0.4	7.6	4.6	0.12
6A	6.3	2.6	7.4	5.9	0.13
6B	6.0	1.6	8.0	5.8	0.14
5A	6.0	3.2	6.5	6.2	0.16
5B	5.6	1.5	7.3	6.0	0.16
4A	4.8	5.3	6.3	6.4	0.18
4B	2.6	4.75	6.4	6.6	0.21
4C	4.5	0.7	5.6	5.1	0.23
3A	3.0	9.6	6.4	7.95	0.20
3B	1.6	3.0	5.65	8.05	0.29
3C	0.9	0.07	5.4	4.9	0.40
2A	1.4	12.9	5.45	8.0	0.25
2B	0.54	13.4	4.7	10.7	0.28
1A	0	18.6	1.75	7.8	N/A

It is worth mentioning again that the TC doesn't think a tabular approach like this is granular enough for program use.

Note: In early October a bug was reported in BEopt 2.2.0.1, whereby the annual heating demand output was being underreported when an HRV or ERV was present. The underlying zone energy balance and site energies were being calculated correctly. NREL provided a patch, and all the selected cost-competitive points were rerun, along with the PV-start points for each location. It wasn't necessary to rerun the optimizations because the site/source energies were correct and that was the basis for choosing the points. The median correction to the heating demand was +5% and the largest was +25% (in Chicago). The patch also addressed a known problem with the reporting of the cooling demand, which for this study was being worked around by calculating it from site cooling and nominal SEER. Therefore, the numbers and formulas reported here, for annual heat demand and cooling demand, are corrected, except in Table 7 and Figure 9. Another change in the patch was that duct losses were excluded from the reported demand. Because the B10 benchmark has duct losses and the upgraded houses do not, this caused the percentage reductions in the annual demands to calculate lower. Future versions are expected to have duct losses broken out in the report.

Table 9: Zone median space conditioning targets, by PV-start rule

Zone	Specific space heating demand [kBtu/sf-iCFA.yr]	Specific space cooling demand [kBtu/sf-iCFA.yr]	Peak heating load (manual J) [Btu/sf-iCFA.hr]	Peak cooling load (manual J) [Btu/sf-iCFA.hr]	Recommended maximum window U (winter comfort) [Btu/h.sf.F]
8	13.2	0.2	8.4	5.0	0.10
7	7.9	0.4	7.6	4.7	0.12
6A	7.6	2.0	7.5	5.9	0.13
6B	8.6	0.8	8.6	5.9	0.14
5A	8.5	2.9	7.4	6.2	0.16
5B	6.5	0.8	7.5	5.9	0.16
4A	6.4	4.9	6.9	6.4	0.18
4B	4.6	2.9	6.7	6.4	0.21
4C	6.7	0.4	6.1	5.2	0.23
3A	4.2	8.9	7.1	8.3	0.20
3B	3.2	3.4	6.2	8.5	0.29
3C	3.1	0.15	6.05	4.9	0.40
2A	2.2	13.0	6.4	8.6	0.25
2B	1.6	12.5	5.6	11.7	0.28
1A	0	21.0	2.2	9.1	N/A

Statistical smoothing

To simplify the results into rules that can be applied everywhere, the resulting space conditioning data was fitted to statistical models in terms of the following independent variables:

- Heating degree-days, base 65 degrees F
- Cooling degree-days, base 65 degrees F
- Heating design dry-bulb temperature, 99.6%
- Cooling design dry-bulb temperature, 0.4%
- Dehumidification design humidity ratio, 0.4%
- Annual global solar radiation
- Electricity price, marginal, state average (city-by-city for Canada)

Electricity price data came from BEopt for US locations, and utility web sites for Canadian cities. Annual global solar radiation is from PHPP-format climate data files generated with Meteonorm. All the other data is from the ASHRAE Fundamentals 2013 data CD.

Statistical analysis was performed using JMP 11.2.0. For each of the four responses (annual heating demand, annual cooling demand, peak heating load, and peak cooling load), a two-step analysis was done:

1. A screening fit was done, to a model with main effects, 2-way and 3-way interaction terms, and quadratic terms.

2. The effects were rank ordered consistent with the Pareto principle and a simplified model was fitted using only the strongest terms. The goal for the simplified models is that the remaining effects should be statistically significant, and the model should be somewhat understandable.

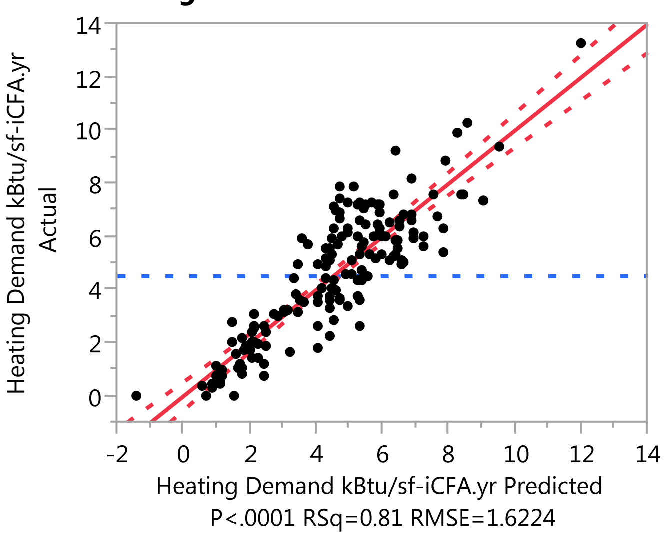
An example of the screening fit is shown in Appendix D, for the peak-cooling load.

The simplified formulas have the effect of "smoothing" over "scatter" caused by: the "lumpiness" of the option upgrades in BEopt, and possible human inconsistency in choosing the cost-competitive points. Of course, there is residual lack-of-fit; the independent variables are not perfect predictors, but the R-squared numbers are reasonable.

The final fits are shown below for all four space conditioning criteria. Note that the formulas shown are per square foot of iCFA. Data generated by the formulas is shown in Appendix C, for all the study locations.

In the terminology of the statistics software, "actual" means the values from BEopt at the human-chosen cost-competitive points, and "predicted" means the value calculated from the simplified statistical model.

Annual heating demand



$$SSHD\ \left[\frac{\text{kBtu}}{\text{sf-iCFA}\cdot\text{yr}}\right] = 4.92 + \frac{HDD65\ [\text{F.days}]}{1341} - \frac{Global\ solar\ radiation\ \left[\frac{\text{kWh}}{\text{m}^2\cdot\text{yr}}\right]}{482} - \frac{Electricity\ price\ \left[\frac{\$}{\text{kWh}}\right]}{0.155}$$

Prediction Profiler

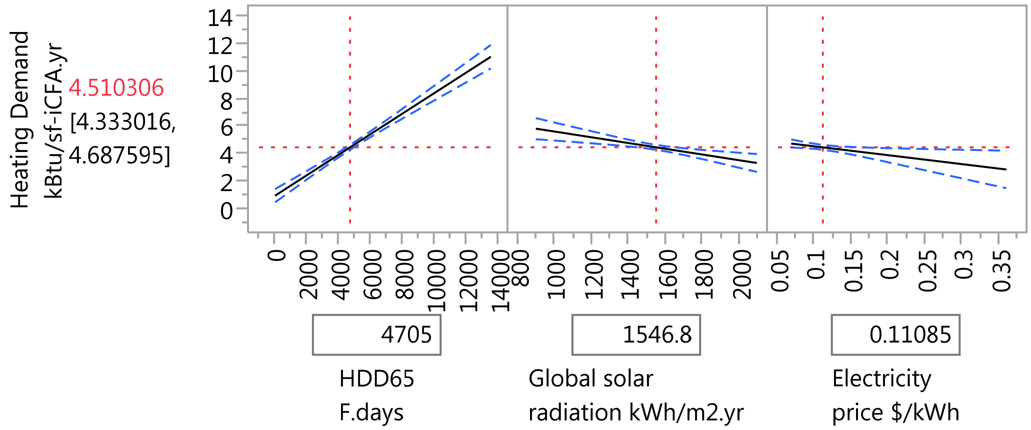
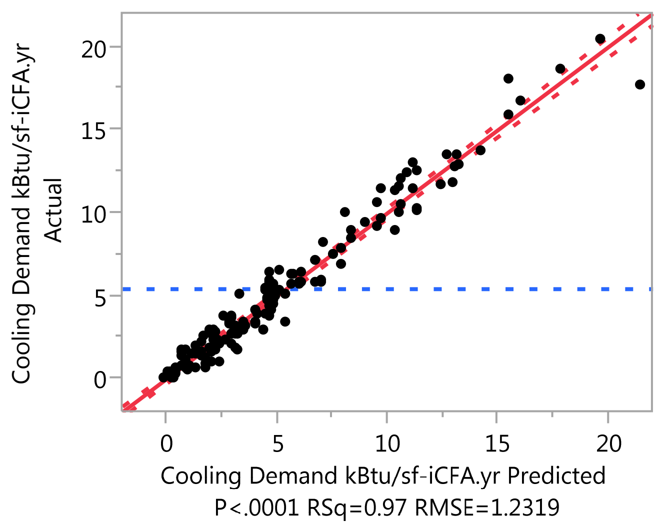


Figure 11. Formula for annual heating demand criterion

The slopes of the lines in the prediction profiler indicate that heating degree-days is the strongest effect. The formula for the annual heat demand target can be explained in words as follows: Start with 4.92 kBtu/sf.yr. For every 1341 heating degree-days at the project location, add 1 kBtu/sf.yr. But there are two take-backs. The more solar resource there is, the better you can do on annual heat demand. For every 482 kWh/m2.yr of global radiation, take back 1 kBtu/sf.yr. Also, the higher the electricity price, the more upgrades you can afford, so for every 15.5 cents per kWh you pay for electricity, take back 1 kBtu/sf.yr.

Annual Cooling demand



$$SSCD\left[\frac{\text{kBtu}}{\text{sf-iCFA}\cdot\text{yr}}\right] = -5.29 + \frac{CDD65\ [\text{F}\cdot\text{days}]}{292} + \frac{DDHR\left[\frac{\text{grains}}{\text{lb}}\right]}{21.6} + \frac{(CDD65 - 1375.7)\cdot(DDHR - 120.04)}{34812}$$

Prediction Profiler

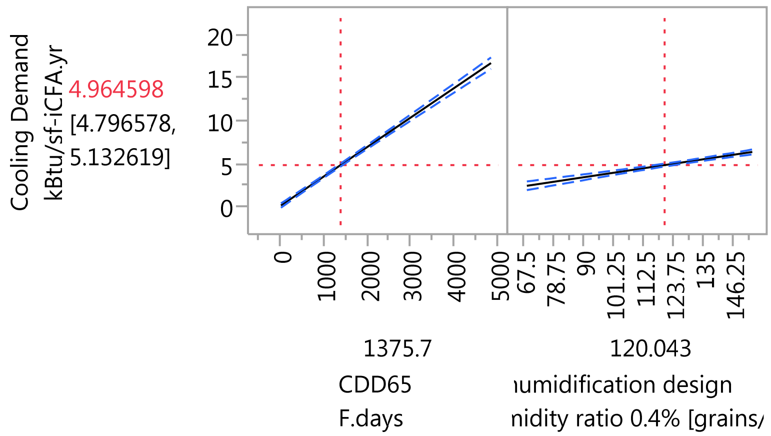
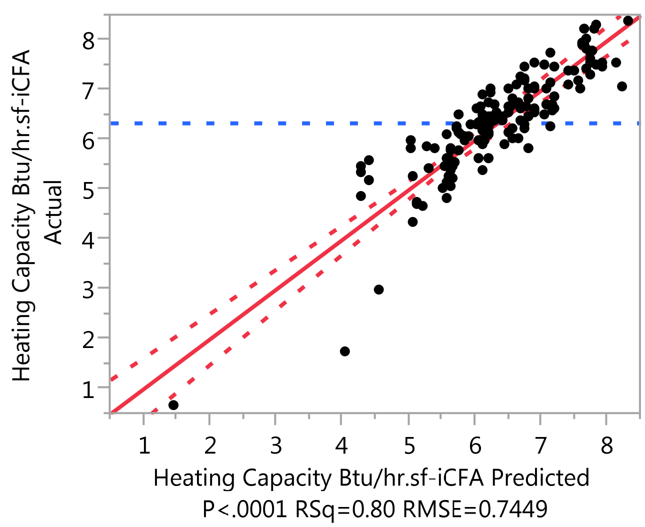


Figure 12. Formula for annual cooling demand criterion

Annual cooling demand turned out to be mostly about cooling degree days, but it was also worth taking into account the humidity, both as an additive term and as a synergistic interaction.

In the coldest climates it was possible for the cooling demand formula to generate negative values, likewise in the warmest climates the heating demand formula might generate a negative value. So the formulas should be implemented with an override to zero. That might still be an overly tight limit, therefore the TC proposes to set the annual demand limits no lower than 1 kBtu/sf.yr.

Heating capacity



$$\textit{Peak heating load (manual J)}\left[\frac{\text{Btu}}{\text{hr}\cdot\text{F}\cdot\text{sf-iCFA}}\right] = 9.0 - \frac{\textit{Design temp}\ [\text{F}]}{13.37} - \frac{HDD65}{5232} - \frac{\textit{Electricity price}\ [\frac{\$}{\text{kWh}}]}{0.125}$$

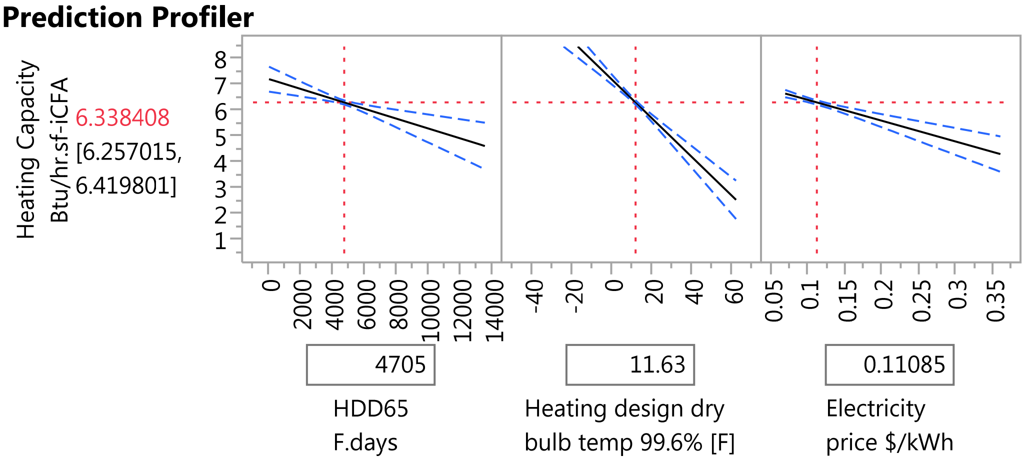
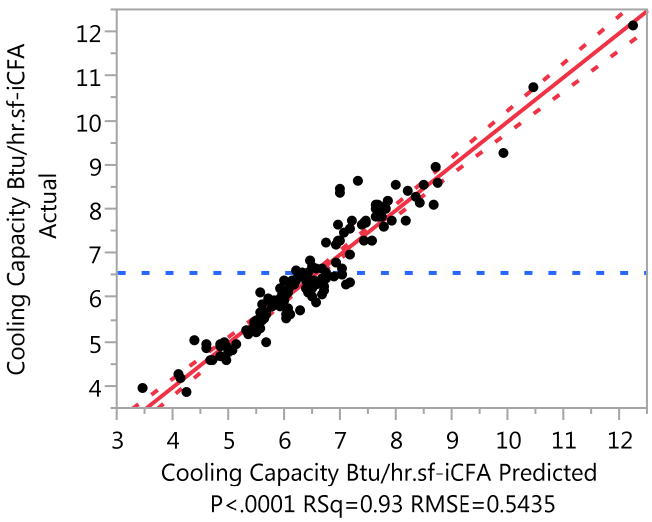


Figure 13. Formula for peak heating load criterion

The peak heat load is mainly controlled by the heating design temperature, which makes sense. But there is a take-back from heating-degree days: the limit is tightened the more degree-days there are. This is because upgrades that pay in reducing annual heat demand also work for reducing peak heat load. Again there is a tightening with increasing electricity price.

Cooling capacity



$$Peak\ cooling\ load\ (manual\ J)\left[\frac{\text{Btu}}{\text{hr·F·sf-iCFA}}\right] = -8.12 + \frac{Design\ Temp\ [\text{F}]}{7.32} + \frac{CDD65}{2562} + \frac{DDHR\ \left[\frac{\text{grains}}{\text{lb}}\right]}{86.3}$$

$$+\frac{(CDD65 - 1376)\cdot(Design\ Temp\ F - 92.4)}{27\ 432}$$

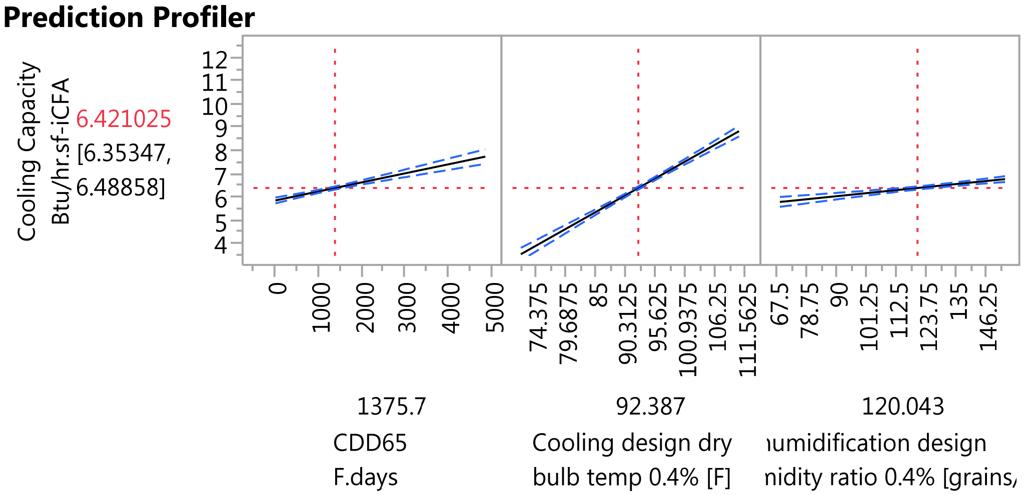


Figure 14. Formula for peak cooling load criterion.

Peak cooling load was the only metric that showed a strong interaction (value of one factor changes the sensitivity to another). The strongest effect was cooling design temperature, but both an additional and a multiplicative allowance were needed with increasing cooling degree-days, as well as some additional relief the higher the dehumidification design humidity ratio.

As alluded to above, when moving out of the central European context, 10 W/m2 peak load, does not always represent the cost-competitive investment in passive measures.

In contrast, every point on the scatterplots created for this study represent a cost-competitive configuration, as determined by BEopt analysis using US construction cost and energy cost data, with human judgement applied point by point. As a result, the annual demands and peak loads both vary with climate and the heating targets also vary with energy price.

5.2 Thermal comfort check

Given that the new criteria tolerate higher peak loads in some cases, there was concern along the lines of, "How fast do the comfort benefits of passive measures decline as the peak load rises above the low-energy-building or supply-air-heating-sufficient level of 10 W/m^2"?

The plan was to address this with some thermal comfort verification checks. The idea was to first compare experimental data on temperature variation in a passive building vs. a detuned version, using a 3-zone WUFI Passive dynamic model (warmest room, coldest room, rest of building), to see if that method could "pick up the signal" of increasing heat distribution difficulty with increased peak load. Then, for a limited subset of the study cases near the cost-optimal points, a similar 3-zone model of the study building would be constructed in WUFI Passive, and human comfort metrics would be checked, e.g. for two different space conditioning distribution configurations: point source and ducted.

Unfortunately none of that fell into place. The experimental data turned out to be not-so-apples-to-apples. Also, despite some weeks of effort, the 3-zone dynamic model in WUFI Passive doesn't reproduce the annual heating demand of the single-zone BEopt model (70% higher), even though the geometry, assemblies, windows, and shading schedule all match and the internal gains, natural ventilation, attic climate, and ground temperatures are all driven by external hourly data files from EnergyPlus. Suspicion is now focused on the zoning and related differences in the mechanical ventilation setup, but the issue is not resolved, and it didn't seem prudent to proceed with comfort evaluation until the energy results matched more closely. The BEopt bug mentioned in 5.1.2 above accounts for some of the discrepancy (probably at least half of it).

Furthermore, the three-zone approach itself needs rethinking, as the original idea (shut off the heat in the cold room and the cooling in the warm room) doesn't realistically address either a normal operation situation or an outage-ride-through scenario. Resolving this problem is a task for future work.

The missing comfort checks are not a significant concern, due to the use of window U-value constraints that were imposed in the study to keep the window surface temperatures above 60 degrees F at the 12-hour mean minimum temperature (usually close to the 99.6% design temperature.) Example hourly output for Chicago is shown below in Figure 15. The window temperatures do mostly stay above 60 degree F. The only irregularity is observed during an early spring heat wave, that occurred outside the time window when the cooling system is enabled per Building America House Simulation Protocol, and therefore it got uncomfortably hot inside. In such a case it might be appropriate to rerun that location with an extended cooling season.

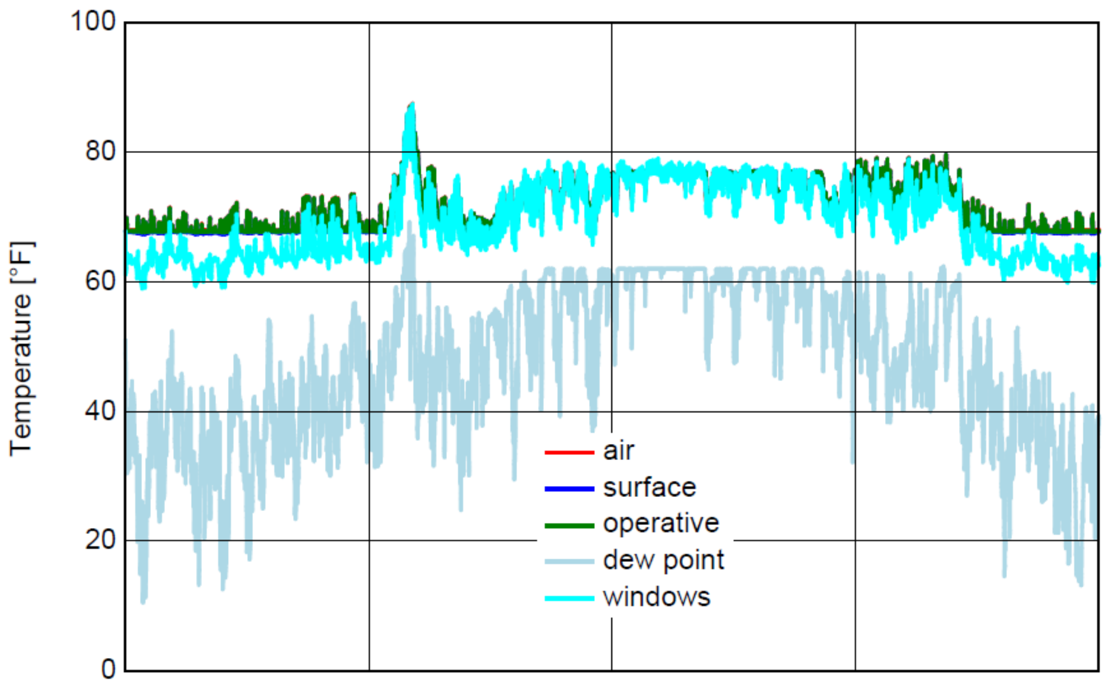


Figure 15. Interior conditions, hourly for the year, Chicago.

5.3 Peak load crossover

Phase 3 of the test plan concerns itself with peak load crossover calculations. It is inconvenient that there are at least three different methods of calculating peak loads:

- WUFI Passive (static mode, like PHPP 2012)
- BEopt / Manual J (also a static calculation)
- WUFI Passive dynamic mode (reports the peak hour of the entire simulation)

BEopt outputs auto-sized heating capacity numbers per Manual J. Unlike WUFI Passive, Manual J does not give any credit for the moderating effect of a long-time-constant building or the previous day's solar gains.

Best practice would probably be to run a dynamic model, look at the duration curve, and pick the 0.4% or 1% level. The TC suggests the two following compliance paths. Either:

1. Calculate peak loads per manual J and use the manual-J based targets as presented above, or
2. Calculate with the static method according to manual-J and multiply the target value from the formulas by 0.6 for heating and 0.7 for cooling to convert to WUFI Passive/PHPP static mode calculation values.

6 Conclusions and future work

The top priorities for future work at this point are:

1. Peak load crossover calculations. At the very least, some more data points need to be collected comparing the methods noted in 5.3 across a range of climates. Longer term, the details of how the moderated design temperatures used in PHPP & WUFI Passive climate data are arrived at needs further analysis. As far as we are aware, this has not been published in open literature, at least in English.
2. Thermal comfort verification. As noted in 5.2, a better way of calculating this benefit or lack thereof needs to be devised, in fact two different ways are probably needed – one for normal operation and another for utility outage scenario. It has also been suggested that the greatest increment of comfort actually occurs between old buildings and new code-minimum buildings – this bears looking into as well. Also, this study did not look at constraining window U-value for summer comfort, only winter.
3. Ground contact calculation protocol (very different between EnergyPlus dynamic and PHPP/WP static.) Anecdotal evidence suggests that the EnergPlus' method predicts a lot less heat loss to the ground than ISO 13370-based static calculations. If so and if EnergyPlus is right, then designers using PHPP/WP are over-insulating their floors. This discrepancy needs to be confirmed and corrected.
4. Climate-dependent, normalized PV utilization curves. One per climate zone is probably granular enough.
5. Studies on relaxing the air-tightness criteria by climate. Again, the air-tightness requirement is driven by moisture risk (energy savings being a side benefit). It stands to

reason that the danger threshold would be climate dependent. Also, it may be appropriate to revisit the field testing protocol: perhaps the test should be done two different ways – one for energy modeling purposes being realistic about leakage in normal operation, and another protocol for durability, focusing on leakage through the assemblies, with more of the nonthreatening things like door thresholds and vent dampers taped off.

6.1 Summary

The proposed adjusted standard has the same high-level organization as before. Adaptations are proposed for all three main pillars.

1. The air-tightness requirement was reconsidered on the basis of avoiding moisture and mold risk, using dynamic hygrothermal simulations to be published elsewhere. The proposed change is from a limit of 0.6 ACH50 to 0.05 CFM50 per square foot of gross envelope area. This allows the airtightness requirement to scale appropriately based on building size. Before, a larger building that met the 0.6 ACH50 requirement could be in actuality up to seven times more leaky than a small single family home that tested the same.

2. The source energy limit was reconsidered on the basis of the global CO_2 emission budget. The following changes are proposed to make the scoring more fair and the calculation more accurate:

    a. Change to a per-person limit rather than per square foot of floor area, at least for residential projects. This follows the fair share principle.

    b. Increase the currently applied German source energy factor for grid electricity from 2.7 to 3.1, consistent with the US national average according to NREL data.

    c. Increase the lighting and miscellaneous plug load defaults to 80% of the RESNET defaults to better reflect actual US usage, and make the internal heat gain calculations consistent with those assumptions.

    d. To absorb the “shock”of the large increase in lighting and plug load defaults, temporarily relieve the source energy limit to 6000 kWh per person per year, tightening to 4200 again within a few years TBD.

    e. Apply the limit to the source energy calculated *net of* the estimated fraction of onsite PV or other renewable electricity generation which is used onsite as it is produced. This puts PV on a similar footing to how solar hot water is currently treated. (For the study building, most of the output of a 2 kW PV array would “count”, depending on the climate.)

3. The space conditioning criteria were reconsidered on the basis of economic feasibility. The proposed change is to

    a. Shift to mandatory, climate-specific thresholds on specific annual heating and cooling demands *and* peak heating and cooling loads, which are set at cost optimal “sweet spot” slightly beyond BEopt’s cost optimum for project’s actual climate for increased resilience benefits. This ensures efficiency measures will have reasonable payback relative to operational energy savings. The peak load thresholds could be adjusted to ensure hourly comfort or the ability of the home to thermally coast through power outages.

b. Simplify the reference floor area from TFA to an inclusive interior-dimension floor area.

By its structure, the proposed standard also retains the feature of the "three hurdles to net zero". The designer's attention is directed first to reducing heating and cooling energy use by passive means (including some mechanical devices,) then to reducing total energy demand by efficient equipment (and some renewables,) and finally to net zero by more renewable generation.

6.2 Conclusions

As passive house standard adaptations go, the one described here is relatively far-reaching. Nevertheless it retains all defining characteristics of a "passive" building. The goal has been to make this reworking rational and principled, as well as reasonably diligent and respectful of historical passive house values. (Some more radical surgeries were proposed but didn't make consensus.)

As in all the previous work, the standard described here keys on low peak load, which serves as a proxy for two kinds of benefits – comfort in normal operation and resilience to outages. Looking further to the future, it might be possible (and better) to develop metrics that get at those benefits more directly, and set criteria on those instead of annual and peak heating and cooling loads.

A uniform source energy limit will remain in place – everyone does their part to achieve necessary carbon reductions for the planet. But the space conditioning criteria are to benefit the building owners and occupants and are recalibrated for economic feasibility, which should tend to encourage more passive building projects.

Under the both-and system (limits on peak loads and annual demands), more projects will likely find themselves challenged on peak loads and source energy instead of annual heat demand. It will tend to favor higher occupancy and more efficient forms of housing.

Of course, it would be an exaggeration to claim that this new system would deliver cost-optimality/competitiveness for any particular real project. But it should be much closer; it is more nuanced, and should at least help to avoid pushing designs way out into diminishing returns, or leaving a lot of feasible energy savings on the table. There is a natural tension between performance maximization and cost minimization.

7 Appendix A – Cost Optimization Calculation Protocol

Table 10: PHIUS Technical Committee resolutions

1. Intentionally left blank.
2. Whereas: RESNET defaults for energy use by "televisions and miscellaneous electric loads" are substantially higher than the current equivalent baseline defaults for "consumer electronics and small appliances" in WUFI Passive (the same goes for lighting). The formulas work a bit differently – the baseline formulas are strictly per person, whereas RESNET uses a combination of per-person and per-square foot terms (conditioned floor area, exterior dimensions). While occupants arguably "should be" using a lot less miscellaneous electricity, keeping low defaults is not an effective way of driving occupant behavior because the occupants are not being certified and there are no consequences to them. Rather, the standards influence the designer and unrealistically low defaults actually create a false incentive – they give too much latitude. Even so, it is reasonable to posit that passive building residents are to some degree, on average, more energy-conscious than usual. Also, current RESNET protocol is based on a five year old study which occurred at the peak of miscellaneous energy consumption. Therefore: For residential projects, the standard defaults for Miscellaneous Electrical and Lighting Demand will increase to (notionally) 80% of RESNET levels [RESNET 2013].
3. Commenters opined that in doing economic analysis, climate is not the only thing that varies from place to place. Energy costs do as well. Because it is convenient to do in BEopt, it should be considered as well. Energy costs will be taken as the state average, or the open EI utility-by-utility rates TBD, rather than national average.
4. The "optimal curve" data set includes both a reference case and a starting point. The reference case for the economic analysis is to always be the B10 benchmark (~ IECC 2009, which is climate-dependent somewhat).
5. The starting point is that the building is constructed air-tight (0.6 ACH50), with ducts inside, and is operated as a passive house in that the occupants are credited with some awareness of how to operate interior blinds and natural ventilation. Also, the thermostat settings will be altered to 68 F winter / 77 F summer, that is justified because the windows are constrained for comfort. (Also the building is over-insulated, and air-sealed.).
6. There will be no subsidizing performance upgrades by cheapening finishes. This strategy, while effective if you can get it on a project, is unfair to include in the studies.
7. To assure credibility, assumptions that may lead to skewed results, financial parameters particularly, should be avoided. Conservative values are assumed for the following parameters:

Mortgage 30 years at 5.4%, down payment 20%, inflation 2.4%, real discount rate 1.95%, project time horizon 30 years, real escalation rate for electricity 1.04%, real escalation rate for gas 0.64% (if needed, see point 13).
8. Knobs the optimizer is allowed to turn will include both passive measures and space-conditioning equipment, to get a true picture on balancing the investment between the two. Update: Also solar hot water (40 or 64 sf) and the option of a 2 kW PV array, to get a better sense of where the source energy is coming out.
9. Window technology is to be constrained by comfort considerations, climate-dependent. The solar heat gain coefficient will be the same on all sides of the study building as differential SHGC is considered impractical in the field.
10. Window area is to be fixed at 15% of wall area, which is equivalent to the BA benchmark.
11. Optimizer to be given some limited ability to choose window distribution: three choices - equal N25, E25, S25, W25; northerly N40, E20, S20, W20; southerly N20, E20, S40, W20.
12. Winter shading reduction factor to be 0.8*0.95 = 0.76. Summer shading reduction factor to be 0.8*(0.2+0.7)/2 = 0.36.
13. Study building to be all-electric. Aligns with net-zero-ready.
14. Foundation to be slab on grade. (Basements were experimented with for hot-dry climate in a preliminary study. It made less difference to the upgraded house than to the benchmark, and so was dropped.) Ceiling to be vented attic, cellulose.
15. Wall type to be exterior rigid foam. For appearances' sake, notionally EPS instead of polyiso. [stud wall + insulation?]
16. Also for appearances sake, the study building is to be 26x40 feet instead of 26x41.
17. The statistical fractions of spa heaters, pool pumps etc. are removed from the study building. While they exist in the benchmark, it is simpler for the purposes of this study to zero them out.

Table 11: BEopt input – options screen, example for Chicago

Option	Reference, B10 Benchmark	Optimization options	Left at reference, reset from ref, or knob.
Building			
Orientation	North	North	Ref
Neighbors	None	at 20 feet (east and west)	Reset
General Operation			
Heating Set Point	71 F	68 F	Reset
Cooling Set Point	76 F	77 F	Reset
Humidity Set Point	60 % RH	60 % RH	Ref
Natural Ventilation	Benchmark - Monday Wednesday Friday	Year round	Reset
Interior Shading	Benchmark - summer & winter = 0.7	Summer 0.36, winter 0.76	Reset
Walls			
Wood Stud	R-13 fiberglass Grade 1, 2x4 16 in OC	R-13 2x4 16 OC	Reset
Wall Sheathing	OSB+R5 XPS	OSB plus up to R-48 polyiso	Knob
Double Wood Stud			
Exterior Finish	Vinyl, light (0.3)	Vinyl, light (0.3)	Ref
Ceiling/Roof			
Unfinished Attic	R-38 cellulose, vented	R-38 to R-120 cellulose, vented	Knob
Roof Material	asphalt shingles, medium (0.85)	asphalt shingles medium, (0.85)	Ref
Radiant Barrier	None	None	Ref
Foundation/Floors			
Slab	2ft R10 perim R5 gap XPS	perimeter /exterior options plus whole-slab up to R40	Knob
Carpet	80% Carpet	80% Carpet	Ref
Thermal Mass			
Floor Mass	Wood surface	Wood surface or 2-in gyp crete	Knob
Exterior Wall Mass	1/2 inch drywall	1/2 in, 5/8, or double 1/2 in drywall	Knob
Partition Wall Mass	1/2 inch drywall	1/2 in, 5/8, or double 1/2 in	Knob

Option	Reference, B10 Benchmark	Optimization options	Left at reference, reset from ref, or knob.
		drywall	
Ceiling Mass	1/2 inch drywall	1/2 in, 5/8, or double 1/2 in drywall	Knob
Windows			
Window Areas	15% F25 B25 L25 R25, casement size	15% F25 B25 L25 R25, F40 else 20, B40 else 20	Knob
Window Tech	Double pane U=0.35 SHGC=0.44	Triple pane: U= 0.18 to 0.13	Knob
Eaves	2 Ft	2 ft or 3 foot	Knob
Overhangs	None	None 2ft, all stories, all windows 2ft, 1st story, all windows 2ft, 1st story, back windows (S)	Knob
Air flow			
Air Leakage	7 ACH 50, 0.5 shelter coefficient	Reference or 0.6 ACH50	Reset
Mechanical Ventilation	Exhaust	Exhaust, HRV 60%, HVR 70%, ERV 83%, ERV 92%	Knob
Space Conditioning			
Air source heat pump	SEER 13, HSPF 7.7	None	Reset
Electric baseboard	None	100% efficient	Reset
Ducts	15% leakage, R-8	In finished space	Reset
Mini-split heat pump	None	SEER 14.5, 8.2 HSPF, SEER 21, 10.7 HSPF, or SEER 27, 11.5 HSPF	Knob
Ceiling Fan	Benchmark	Hi efficiency	Reset
Dehumidifier	None	None, or autosize standalone	Knob
Water heating			
Water heater	Electric benchmark	Electric 0.92, 0.95, or 0.99 tankless, HPWH 50 gal 140F inside, HPWH 80 gal inside.	Knob
Distribution	Uninsulated, trunk-branch, copper	R-2, trunk-branch, copper, demand-recirc	Reset
Solar Water Heating	None	None, 40 sf, 64 sf	Knob

Option	Reference, B10 Benchmark	Optimization options	Left at reference, reset from ref, or knob.
Lighting	Benchmark (1764 kWh/yr)	767 kWh/yr (80% RESNET), costs for 100% CFL	Reset
Major Appliances			
Refrigerator	Benchmark (434 kWh/yr)	384 kWh/yr	Reset
Cooking Range	Benchmark (electric)	Benchmark (electric)	Ref
Dishwasher	Benchmark	318 kWh/yr	Reset
Clothes Washer	Benchmark	EnergyStar	Reset
Clothes Dryer	Benchmark (electric)	Electric	Ref
Miscellaneous			
Other electric loads	Benchmark (2228 kWh/yr)	2048 kWh/yr (80% RESNET)	Reset
Other hot water loads	Benchmark	Benchmark	Ref
Power Generation			
PV System	None	None or 2.0 kW	Knob

Table 12: BEopt input, geometry screen

40x26 ft., 2 stories, above grade, short side south. (Same for all locations) First floor 9 feet high, 2nd floor 10 feet high.

Input	Value	Units	
Total Finished Floor Area	2080	Sq. ft.	(Nominal TFA 1560 sf)
Bedrooms	3		
Baths	2		

7.1 Custom BEopt options and cost overrides

The only actual cost override used was on HRV/ERV cost (higher). Window cost, ceiling, wall insulation and slab insulation costs were extrapolated for higher-performing options. The exterior-foam wall assembly was given two increments in labor cost to represent attaching multiple layers of rigid foam.

Ventilator cost data

Built-in BEopt options for HRV's and ERV's were limited and the costs seemed too low, so the following data was collected mostly by internet search. (Model names have been anonymized; the first four entries are built-in BEopt options.) Because the performance depends on both the thermal and electrical efficiency, it isn't obvious at a glance how to rank order the options. A preliminary optimization run was done in BEopt on this factor alone, and a subset of eight choices on and near the optimal path was selected for use in the main study. Those entries are in boldface type. The listed cost includes BEopt's default $618 for installation labor.

Table 13: Ventilator cost data

Option	Cost (material+labor)
Exhaust	$245
HRV, 60%	$914.34
HRV, 70%	$914.34
ERV, 72%	$878.65
HRV 65, 0.86 W/cfm	$1401
ERV 67, 0.86 W/cfm	$1567
ERV 67, 0.46 W/cfm	$2522
ERV 71, 0.93 W/cfm	$1748
HRV 71, 0.63 W/cfm	$1517
HRV 75, 0.49 W/cfm	$2243
HRV 82, 1.01 W/cfm	$2759
ERV 83, 0.72 W/cfm	$2718
HRV 88, 0.31 W/cfm	$2813
HRV 91, 0.29 W/cfm	$4418

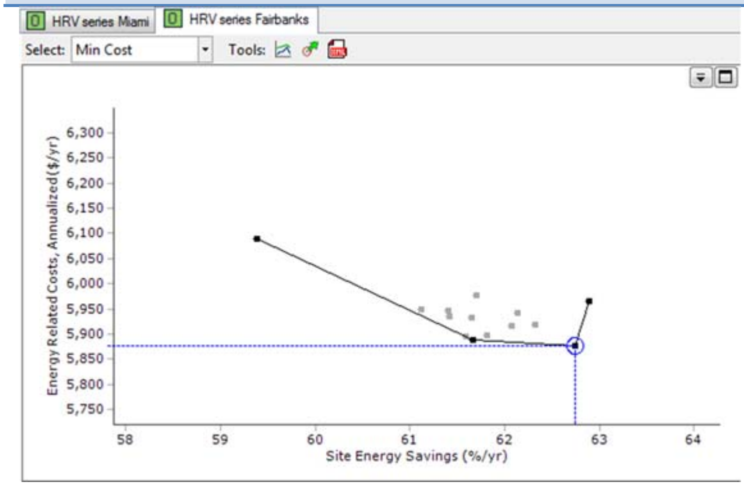


Figure 16. Preliminary optimization run to screen ventilator options.

Window cost extrapolation

The extrapolation to higher-performing windows is shown in the figure below.

Insulated frame, BEopt data

panes	SHGC	whole window U	R	$/sf window
2	hi	0.32	3.13	15.3
2	med	0.3	3.33	16.79
2	lo	0.29	3.45	17.96
2	hi	0.29	3.45	18.31
2	med	0.27	3.70	21.5
2	lo	0.26	3.85	24.06
3	hi	0.21	4.76	45.95
3	lo	0.19	5.26	57.35
3	hi	0.18	5.56	66.63
3	lo	0.17	5.88	68.45
		Extrapolate		
		0.16	6.25	77.97
		0.15	6.67	86.82
		0.14	7.14	96.93
		0.13	7.69	108.59
		0.12	8.33	122.20
		0.11	9.09	138.29

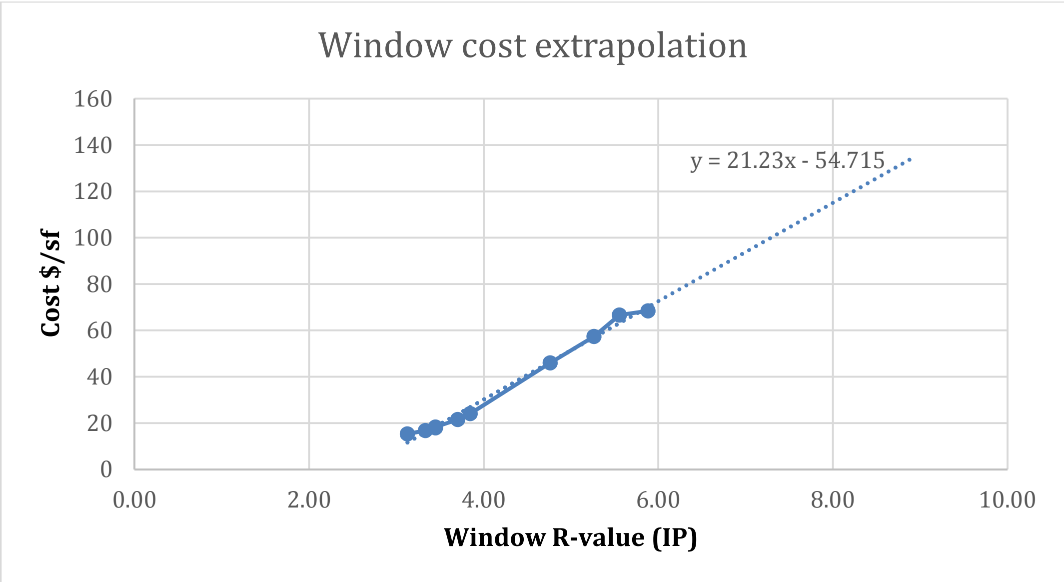
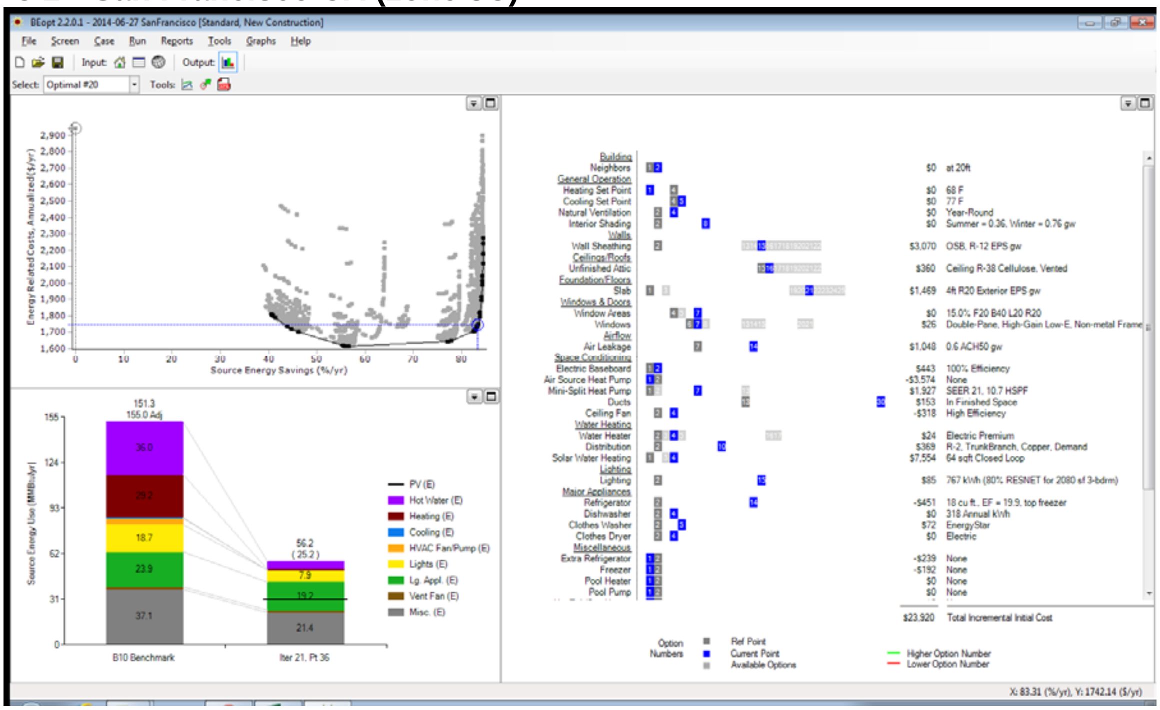


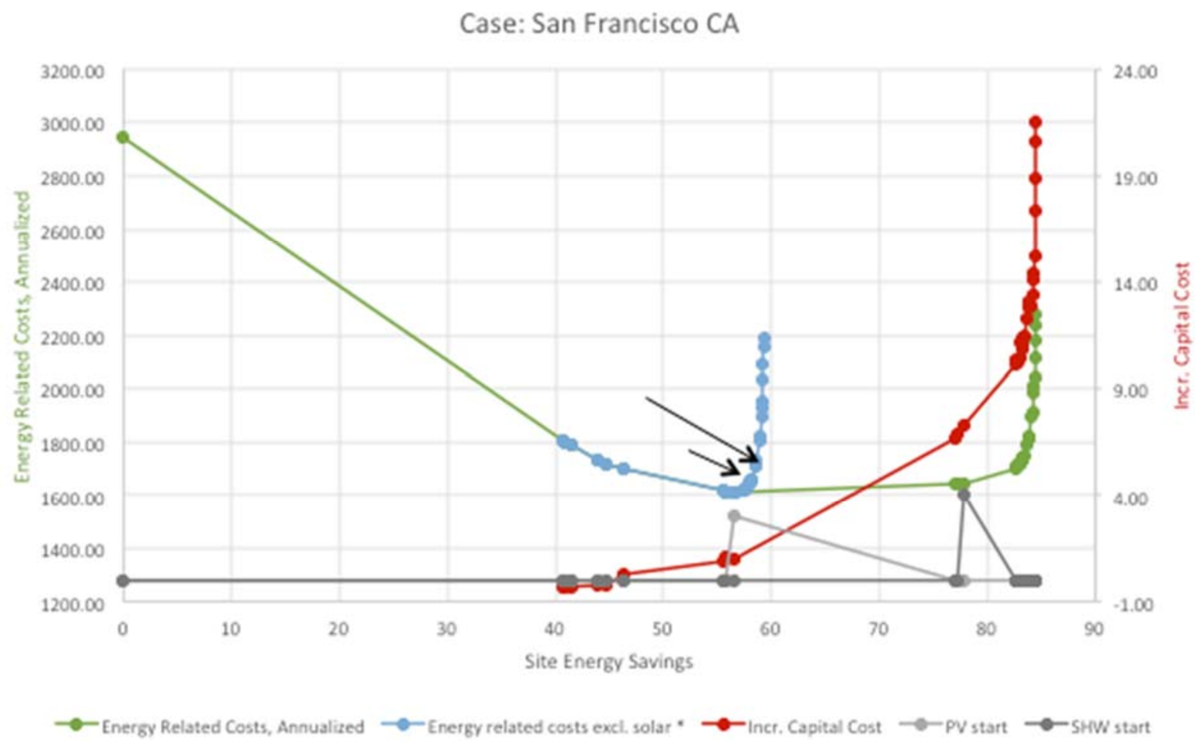
Figure 17. Cost extrapolation for windows.

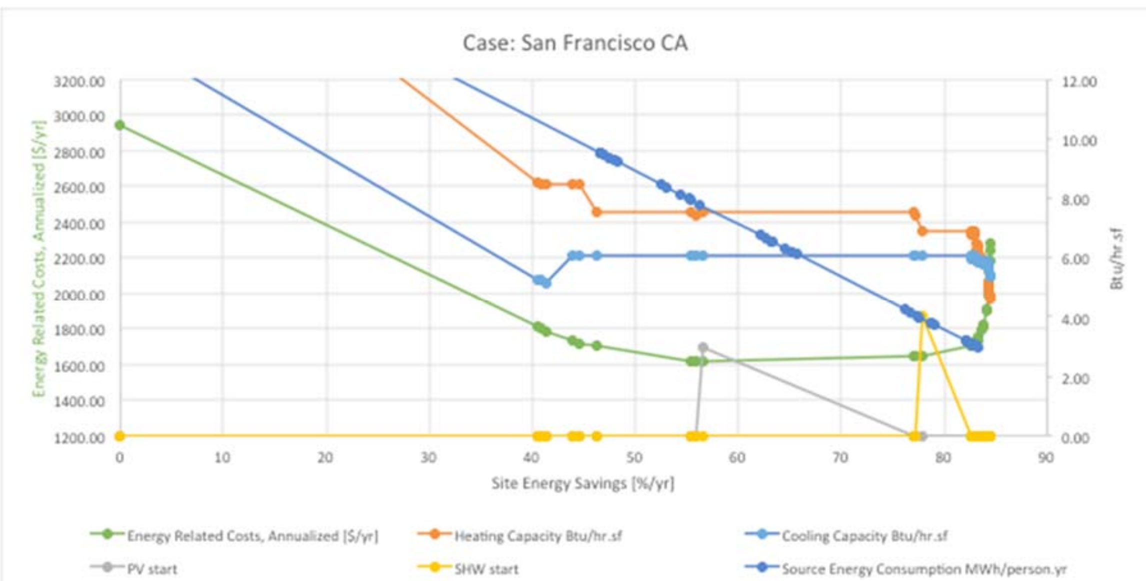
8 Appendix B – Cost curves and BEopt output for four example locations.

Black arrows indicate the chosen “cost-competitive” points.

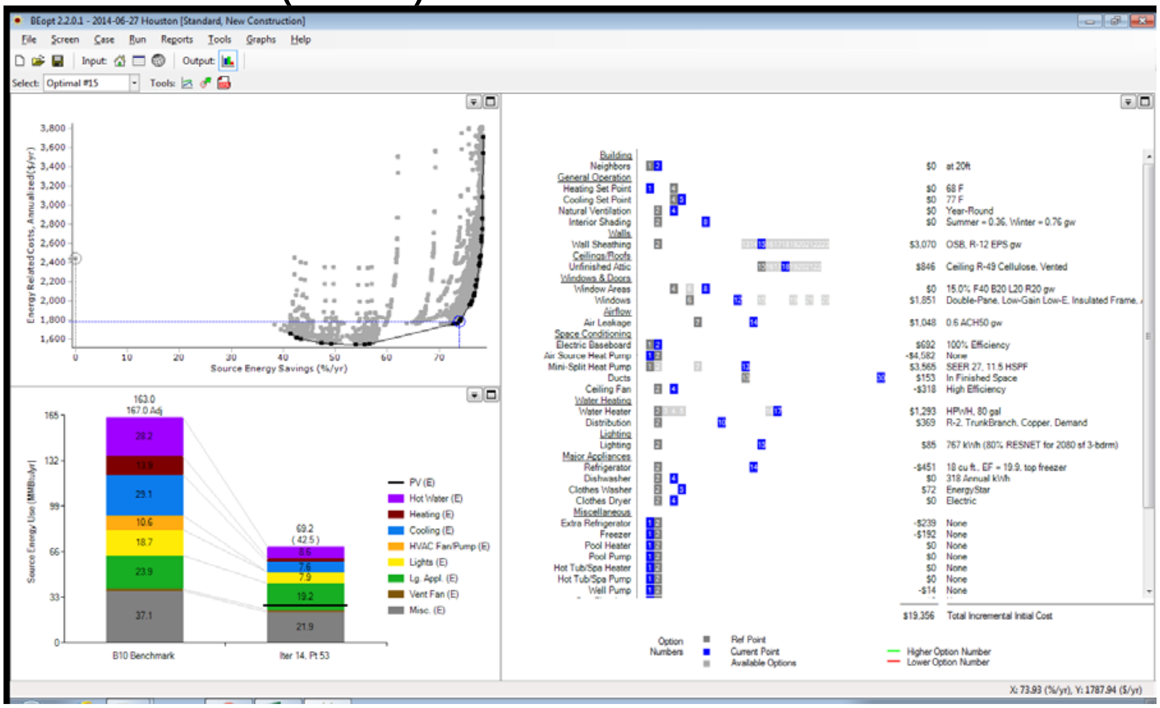
8.1 San Francisco CA (zone 3C)

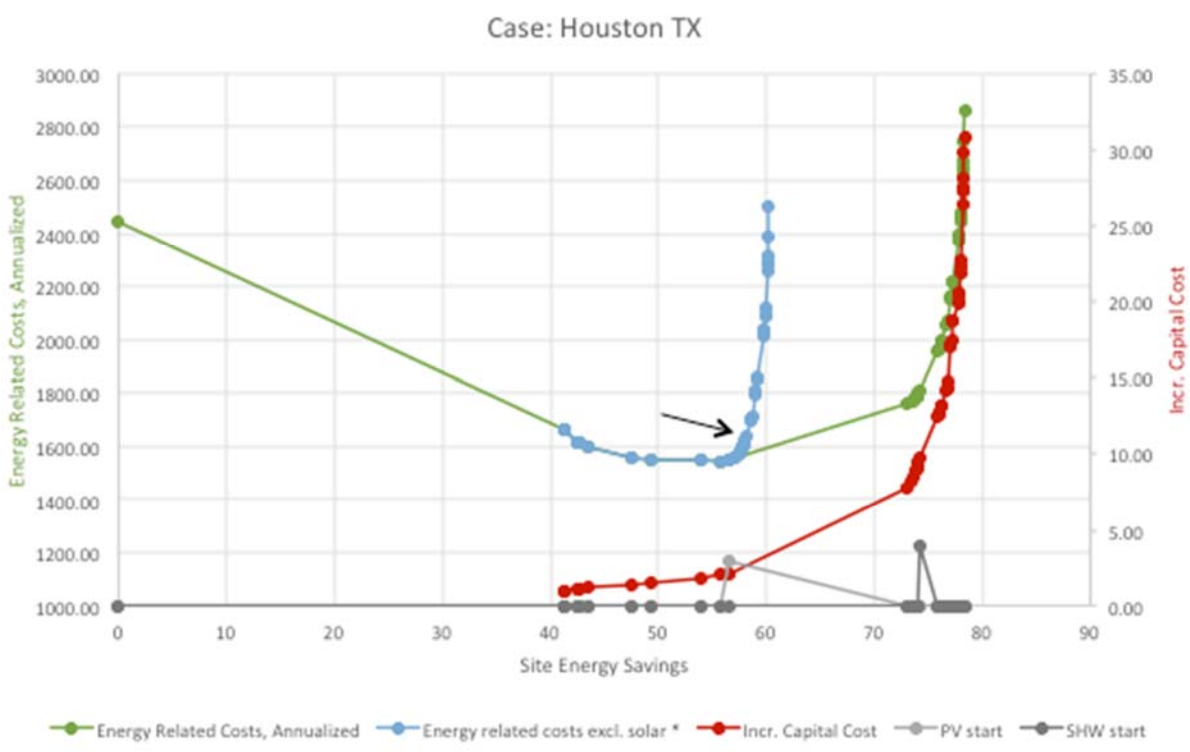



Case: San Francisco CA
Energy Related Costs, Annualized
Incr. Capital Cost
Site Energy Savings
Energy Related Costs, Annualized
Energy related costs excl. solar *
Incr. Capital Cost
PV start
SHW start

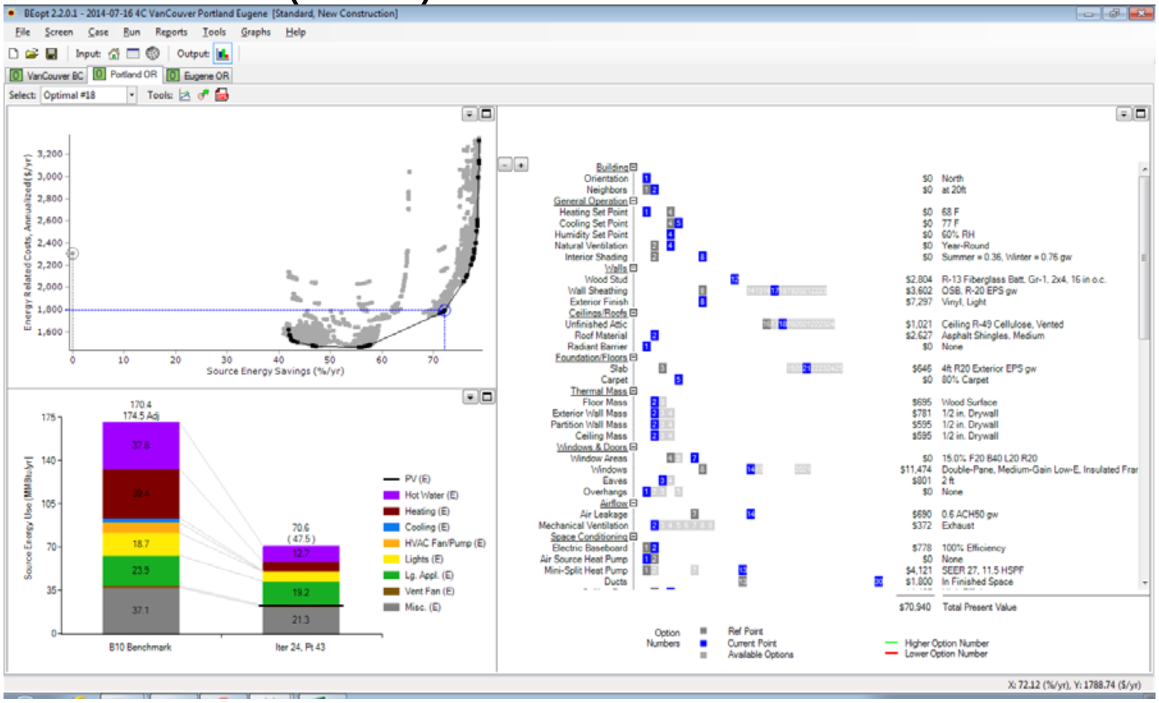

Case: San Francisco CA
Energy Related Costs, Annualized [$/yr]
Btu/hr.sf
Site Energy Savings [%/yr]
Energy Related Costs, Annualized [$/yr]
Heating Capacity Btu/hr.sf
Cooling Capacity Btu/hr.sf
PV start
SHW start
Source Energy Consumption MWh/person.yr

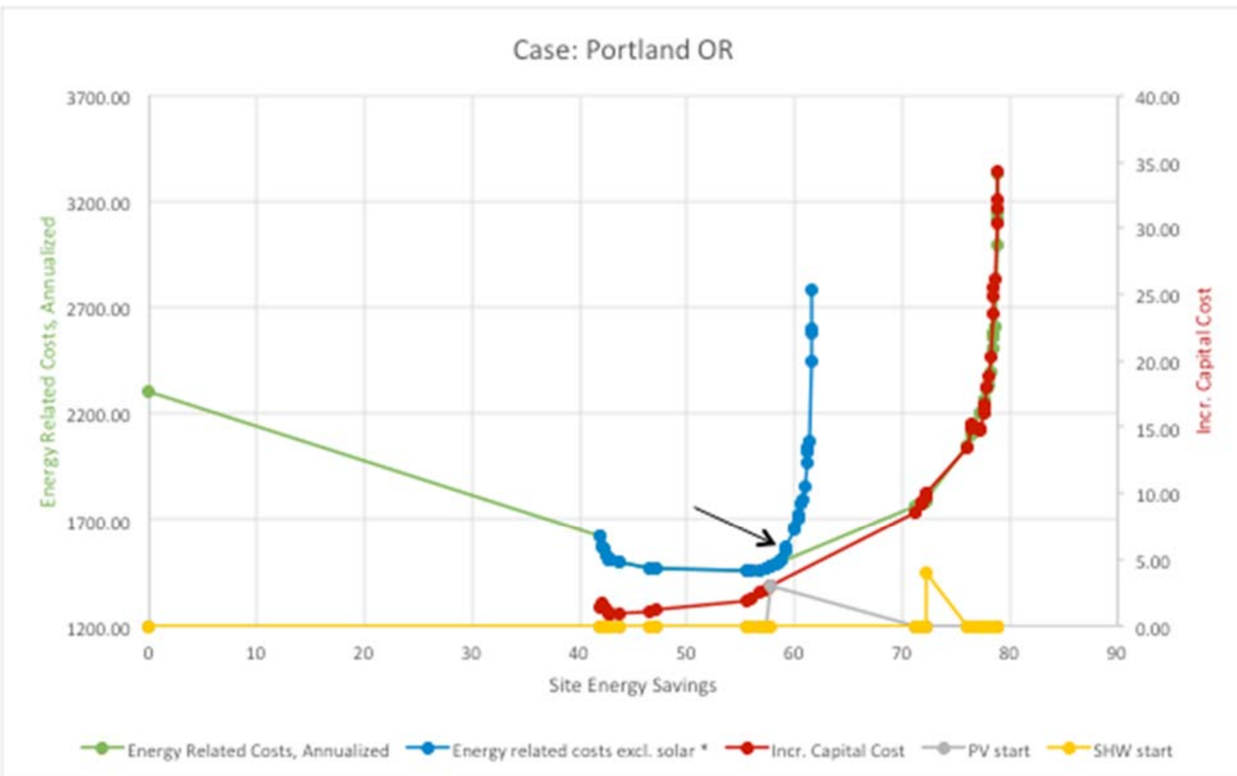
8.2 Houston TX (zone 2A)

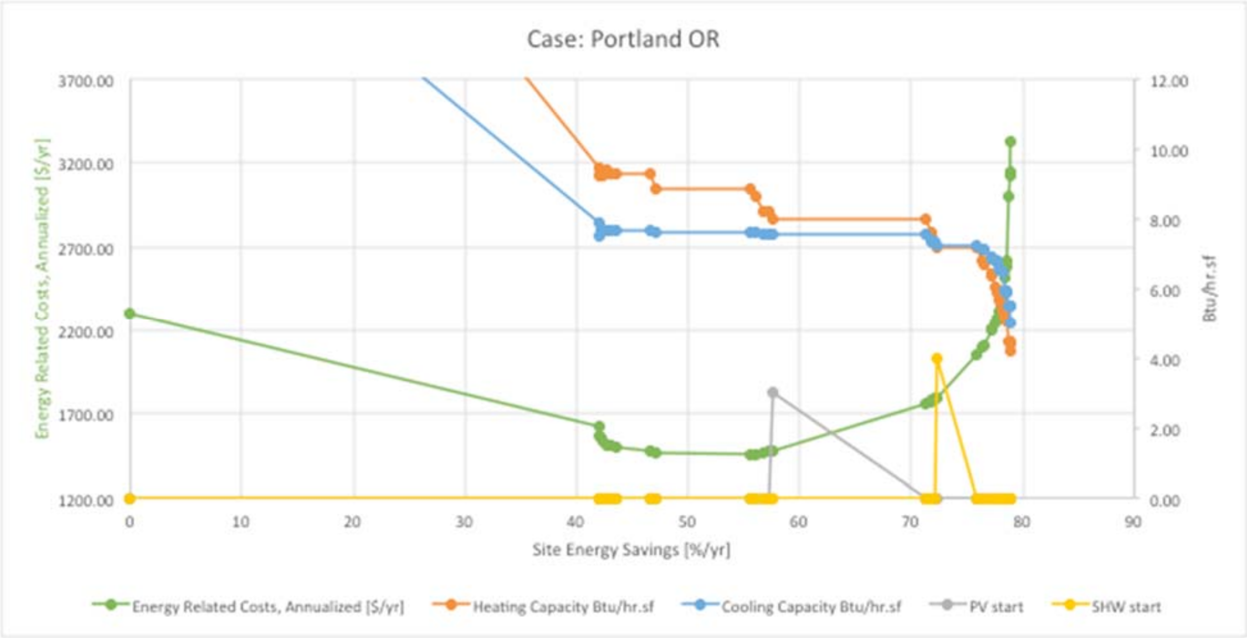




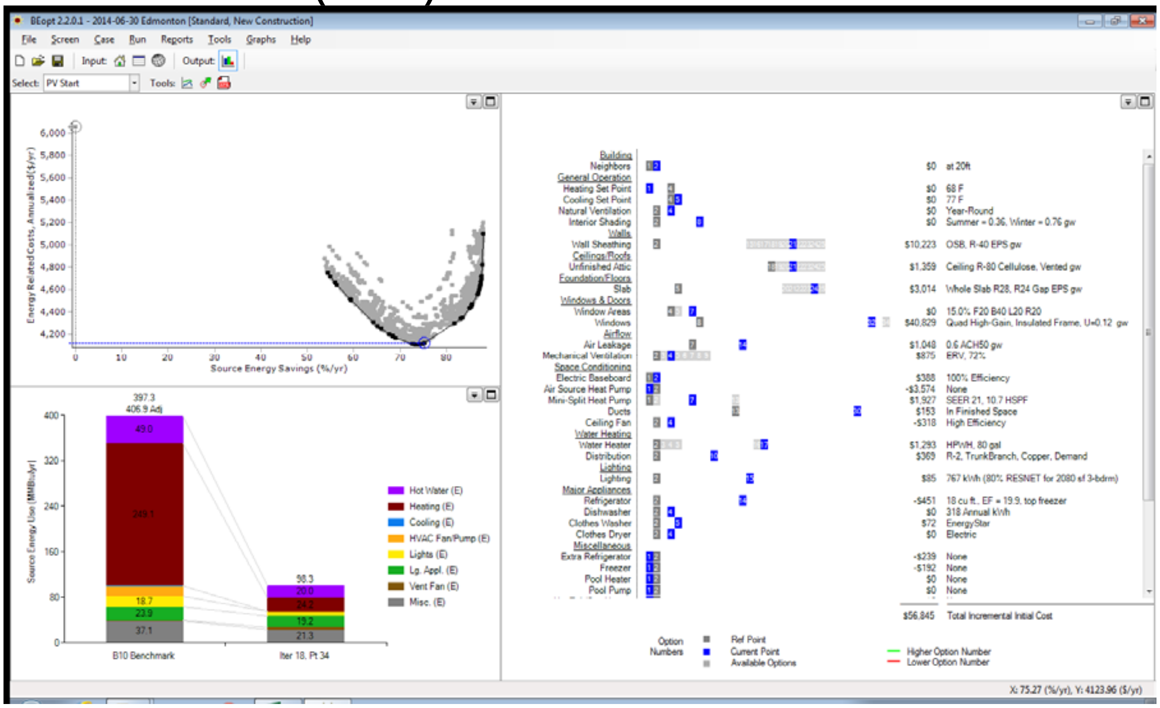
8.3 Portland OR (zone 4C)

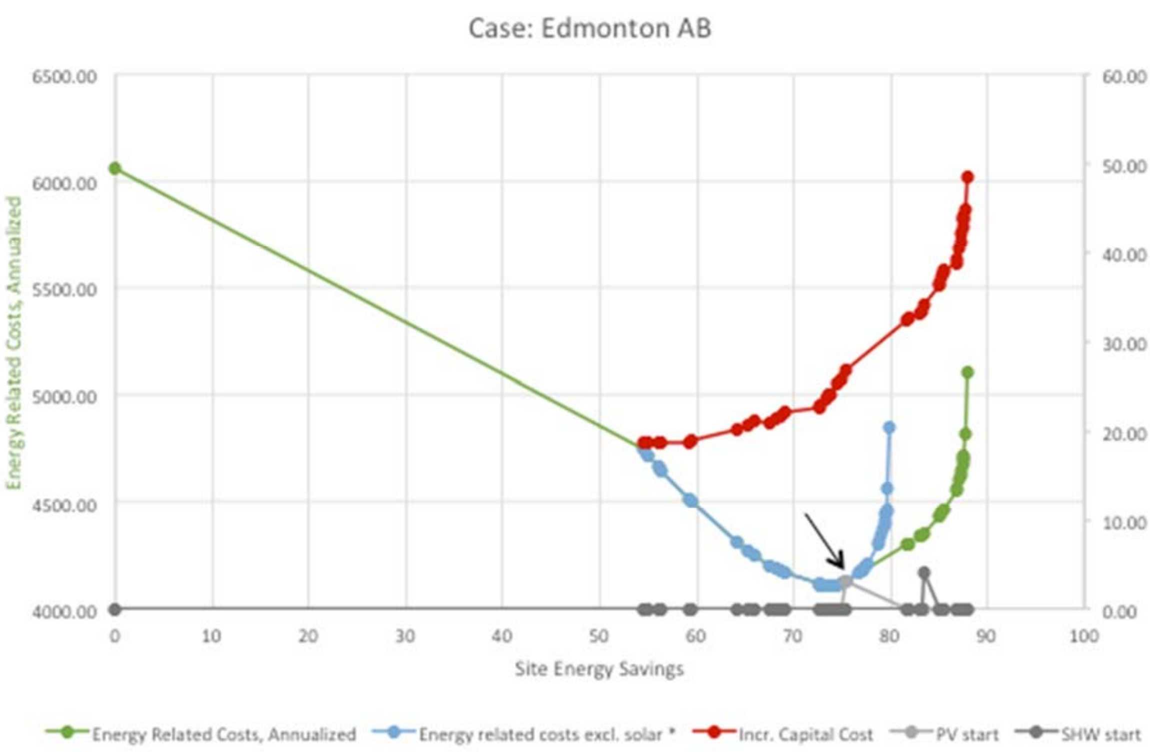





Case: Portland OR
Energy Related Costs, Annualized [$/yr]
Btu/hr.sf
Site Energy Savings [%/yr]
3700.00
3200.00
2700.00
2200.00
1700.00
1200.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
10
20
30
40
50
60
70
80
90
Energy Related Costs, Annualized [$/yr]
Heating Capacity Btu/hr.sf
Cooling Capacity Btu/hr.sf
PV start
SHW start

8.4 Edmonton AB (zone 7)





9 Appendix C – Space conditioning data table

Zone	City	State	HDD65 F.days	CDD65 F.days	Global solar radiation kWh/m2.yr	12-h mean minimum temp [F]	Heating design dry bulb temp 99.6% [F]	Cooling design dry bulb temp 0.4% [F]	Dehumidification design humidity ratio 0.4% [grains/lb]	Electricity price $/kWh	Annual heating demand kBtu/sf-iCFA.yr	Annual cooling demand kBtu/sf-iCFA.yr	manual J Peak heating load Btu/sf-iCFA.h	manual J Peak cooling load Btu/sf-iCFA.h	PHPP/WP Peak heating load Btu/sf-iCFA.h	PHPP/WP Peak cooling load Btu/sf-iCFA.h	Recommended max window U value (winter comfort) Btu/h.sf.F
7	Calgary	AB	9093	64	1480	-17.32	-19.8	83.5	83.1	0.1228	7.8	1.0	7.8	4.7	4.7	3.3	0.13
7	Edmonton	AB	9356	121	1314	-25.6	-20.5	83	89.7	0.1206	8.4	1.0	7.8	4.7	4.7	3.3	0.12
7	Anchorage	AK	10121	5	894	-9.4	-9.3	71.5	68.2	0.1663	9.5	1.0	6.4	3.5	3.9	2.4	0.14
8	Fairbanks	AK	13517	72	935	-35.5	-43.5	81.3	74.1	0.1663	12.0	1.0	8.3	4.4	5.0	3.1	0.10
3A	Birmingham	AL	2653	2014	1607	13.46	20.5	95.5	138.7	0.1068	2.9	8.4	6.1	7.4	3.7	5.2	0.20
2A	Mobile	AL	1652	2499	1643	24.08	27.7	93.8	146.6	0.1068	2.1	10.9	5.8	7.4	3.5	5.2	0.25
3A	Little Rock	AR	3158	1938	1637	9.5	18.5	95.4	138.9	0.0858	3.3	8.1	6.3	7.3	3.8	5.1	0.18
5B	Flagstaff	AZ	6830	123	1900	-9.4	3.9	85.7	93.2	0.1054	5.4	1.0	6.6	5.0	3.9	3.5	0.14
2B	Phoenix	AZ	923	4626	2094	#N/A	38.7	110.3	120.1	0.1054	1.0	16.1	5.1	12.3	3.0	8.6	#N/A
2B	Tucson	AZ	1416	3273	2065	30.02	31.6	106	118.7	0.1054	1.0	11.3	5.5	9.9	3.3	7.0	0.28
4C	VanCouver	BC	5225	80	1268	21.02	20.9	77.3	84.4	0.1027	5.5	1.0	5.6	4.2	3.4	2.9	0.23
3B	Fresno	CA	2266	2097	1883	29.48	31.4	103.5	94.7	0.1419	1.8	5.7	5.1	8.2	3.0	5.8	0.28
3B	Los Angeles	CA	1295	582	1827	#N/A	44.5	83.7	101.6	0.1419	1.2	1.8	4.3	5.0	2.6	3.5	#N/A
3B	Sacramento	CA	2495	1213	1804	31.64	31.1	100.1	88.9	0.1419	2.1	3.1	5.1	7.0	3.0	4.9	0.30
3B	San Diego	CA	1197	673	1878	#N/A	44.8	83.1	104.7	0.1419	1.0	2.2	4.3	4.9	2.6	3.5	#N/A
3C	San Francisco	CA	2689	144	1718	#N/A	39.1	82.8	80.8	0.1419	2.5	1.0	4.4	4.6	2.7	3.2	#N/A
5B	Boulder	CO	5667	721	1639	-1.48	-1.4	93.9	94.7	0.1021	5.1	2.0	7.2	6.0	4.3	4.2	0.16

5B	Colorado Springs	CO	6160	459	1675	2.3	1.3	90.4	95.5	0.1021	5.4	1.3	6.9	5.6	4.1	3.9	0.16
5A	Hartford	CT	5935	765	1370	5.54	4.1	91.4	124.3	0.1626	5.5	3.0	6.3	6.1	3.8	4.3	0.17
4A	Wilmington	DE	4756	1142	1479	-9.22	13.3	91.9	133.3	0.1271	4.6	4.7	6.1	6.4	3.6	4.5	0.14
2A	Daytona Beach	FL	748	2992	1774	25.16	35.6	92.8	144.2	0.1081	1.1	12.7	5.3	7.4	3.2	5.2	0.25
2A	Jacksonville	FL	1327	2632	1658	21.56	29.4	94.6	142.9	0.1081	1.8	11.1	5.7	7.6	3.4	5.3	0.23
1A	Key West	FL	70	4832	1320	#N/A	54.3	90.9	152	0.1081	1.5	21.4	4.1	7.7	2.4	5.4	#N/A
1A	Miami	FL	126	4537	1754	#N/A	47.6	91.8	148.1	0.1081	1.0	19.6	4.5	7.8	2.7	5.5	#N/A
2A	Tampa	FL	527	3563	1814	#N/A	38.8	92.6	147.7	0.1081	1.0	15.5	5.1	7.6	3.1	5.3	#N/A
3A	Atlanta	GA	2671	1893	1687	12.74	21.5	93.9	133.1	0.1030	2.8	7.5	6.1	7.0	3.6	4.9	0.20
3A	Macon	GA	2263	2179	1683	19.58	23.9	96.9	138.3	0.1030	2.5	9.0	6.0	7.7	3.6	5.4	0.22
2A	Savannah	GA	1761	2455	1677	25.52	27.4	95.5	146.1	0.1030	2.1	10.7	5.8	7.7	3.5	5.4	0.25
1A	Honolulu	HI	0	4679	1925	#N/A	62	89.8	131.2	0.3600	1.0	17.8	1.5	7.2	0.9	5.0	#N/A
5A	Des Moines	IA	6172	1034	1531	-4.9	-5.3	92.5	138.7	0.0995	5.7	4.5	7.4	6.5	4.4	4.6	0.15
5B	Boise	ID	5453	957	1619	5.72	8.7	98.6	77.5	0.0773	5.1	2.1	6.7	6.5	4.0	4.6	0.17
5A	Chicago	IL	6209	864	1380	-5.44	-1.5	91.4	133.3	0.1032	6.0	3.6	7.1	6.3	4.3	4.4	0.15
5A	Fort Wayne	IN	5991	825	1391	-5.26	-0.7	90.8	134.5	0.0961	5.9	3.5	7.1	6.2	4.3	4.3	0.15
5A	Indianapolis	IN	5272	1087	1503	-5.26	2	91	136.8	0.0961	5.1	4.6	7.1	6.3	4.2	4.4	0.15
4A	Wichita	KS	4464	1682	1686	4.1	7.4	100.1	134.2	0.1031	4.1	6.8	6.8	7.8	4.1	5.5	0.17
4A	Lexington	KY	4567	1201	1475	-2.74	8.3	91.6	132.6	0.0866	4.7	4.9	6.8	6.4	4.1	4.5	0.15
4A	Louisville	KY	4201	1459	1347	1.04	9.7	93.3	136	0.0866	4.7	6.0	6.8	6.8	4.1	4.7	0.16
2A	New Orleans	LA	1286	2925	1632	27.86	33.1	93.8	150.6	0.0772	2.0	13.0	5.7	7.7	3.4	5.4	0.27
5A	Boston	MA	5596	750	1408	-1.66	8.1	90.6	122	0.1365	5.3	2.9	6.2	6.0	3.7	4.2	0.16

4A	Baltimore	MD	4552	1261	1490	8.42	14	94	133.2	0.1208	4.5	5.1	6.1	6.7	3.7	4.7	0.18
5A	Detroit	MI	5989	884	1304	2.12	5.2	90.7	126.3	0.1294	5.9	3.5	6.4	6.1	3.9	4.3	0.16
5A	Grand Rapids	MI	6615	639	1388	-10.66	2.2	89.4	128.2	0.1294	6.1	2.7	6.5	5.9	3.9	4.1	0.14
7	Duluth	MN	9325	210	1342	-22	-17.9	84.3	114.4	0.1010	8.4	1.0	7.7	5.1	4.6	3.6	0.12
7	International Falls	MN	9944	218	1261	-28.48	-26.1	86.1	113.9	0.1010	9.1	1.0	8.2	5.3	4.9	3.7	0.11
6A	Minneapolis	MN	7472	765	1401	-19.12	-11.2	90.9	128.3	0.1010	6.9	3.1	7.6	6.1	4.6	4.3	0.12
4A	Kansas City	MO	5012	1372	1588	1.4	2	95.8	145.3	0.0934	4.8	6.1	7.1	7.2	4.3	5.0	0.16
4A	Springfield	MO	4442	1366	1587	1.04	6.6	94.8	135.6	0.0934	4.3	5.6	6.9	6.9	4.1	4.8	0.16
4A	St. Louis	MO	4436	1650	1533	1.04	6.6	95.5	140.6	0.0934	4.5	7.0	6.9	7.2	4.1	5.1	0.16
3A	Jackson	MS	2282	2294	1682	18.32	23.2	96.4	142.9	0.0954	2.5	9.8	6.1	7.7	3.6	5.4	0.22
6B	Billings	MT	6705	630	1504	-7.24	-9.4	94.8	89.3	0.0914	6.2	1.7	7.7	6.0	4.6	4.2	0.14
6B	Helena	MT	7545	395	1461	-9.58	-13	92.9	83.7	0.0914	6.9	1.0	7.8	5.7	4.7	4.0	0.14
4A	Asheville	NC	4144	844	1577	13.1	14.7	88.3	125.8	0.1010	4.1	3.3	6.3	5.8	3.8	4.1	0.20
3A	Charlotte	NC	3065	1713	1633	19.58	21	94.3	130.8	0.1010	3.2	6.7	6.0	7.0	3.6	4.9	0.22
4A	Raleigh	NC	3275	1666	1590	13.28	19.6	94.8	134.8	0.1010	3.4	6.8	6.1	7.1	3.7	4.9	0.20
6A	Bismarck	ND	8396	546	1440	-20.02	-18.5	93.9	121.3	0.0810	7.7	2.2	8.1	6.3	4.9	4.4	0.12
5A	Grand Island	NE	6081	1037	1605	-7.96	-4.3	95.7	136.2	0.0924	5.5	4.4	7.4	6.9	4.4	4.8	0.14
5A	Omaha	NE	5981	1093	1532	-5.26	-6.1	94	135.3	0.0924	5.6	4.6	7.6	6.7	4.5	4.7	0.15
4A	Atlantic City	NJ	4913	1014	1480	13.64	11.4	92.2	132.5	0.1466	4.6	4.2	6.0	6.4	3.6	4.5	0.20

6A	Saint Johns	NL	8727	54	1169	3.92	4.3	76.3	100.1	0.1118	8.3	1.0	6.1	4.3	3.7	3.0	0.17
4B	Albuquerque	NM	3994	1370	1926	20.66	18.2	95.3	100	0.1011	3.3	4.0	6.1	6.6	3.6	4.6	0.23
5B	Elko	NV	7115	358	1722	-13	-4.1	94.6	74.9	0.1098	6.0	1.0	7.1	5.7	4.2	4.0	0.13
3B	Las Vegas	NV	2015	3486	2034	28.58	31	108.4	103	0.1098	1.5	10.4	5.4	10.5	3.2	7.3	0.27
5B	Reno	NV	5043	791	1833	1.4	12.1	96.3	76	0.1098	4.2	1.7	6.2	6.1	3.7	4.3	0.16
5A	Albany	NY	6562	619	1408	0.5	-0.9	89.2	122.5	0.1634	5.8	2.4	6.5	5.8	3.9	4.1	0.16
5A	Buffalo	NY	6584	590	1359	3.2	3	88	124.6	0.1634	6.0	2.4	6.2	5.7	3.7	4.0	0.17
4A	New York City	NY	4555	1259	1438	6.44	13.9	92.4	127.9	0.1634	4.3	4.9	5.8	6.5	3.5	4.5	0.18
5A	Syracuse	NY	6577	594	1366	-1.48	-1.2	89.2	121.1	0.1634	5.9	2.3	6.5	5.8	3.9	4.0	0.16
5A	Cleveland	OH	5850	774	1377	-1.84	4.1	89.7	127.3	0.1078	5.7	3.1	6.7	6.0	4.0	4.2	0.15
5A	Columbus	OH	5255	1015	1392	0.14	5	91.1	129.1	0.1078	5.3	4.1	6.8	6.2	4.1	4.4	0.16
3A	Oklahoma City	OK	3487	2047	1620	9.86	12.5	99.5	130	0.0871	3.6	7.9	6.7	7.9	4.0	5.6	0.19
3A	Tulsa	OK	3455	2051	1661	6.8	13.2	99.4	136.6	0.0871	3.5	8.4	6.7	8.0	4.0	5.6	0.18
6A	Ottawa	ON	8142	428	1377	-15.16	-11.5	87.1	115.7	0.1406	7.2	1.6	7.2	5.5	4.3	3.8	0.13
5A	Toronto	ON	7006	526	1381	0.86	-0.5	88.5	119.7	0.1380	6.4	2.1	6.6	5.7	4.0	4.0	0.16
4C	Astoria	OR	4949	20	1185	27.86	27.5	76.9	81.4	0.0906	5.6	1.0	5.3	4.1	3.2	2.9	0.27
4C	Eugene	OR	4638	270	1355	22.64	23.4	91.7	84.8	0.0906	5.0	1.0	5.6	5.5	3.4	3.9	0.24
4C	Portland	OR	4214	433	1286	28.04	25.2	91.4	87	0.0906	4.8	1.1	5.6	5.6	3.3	3.9	0.27
4C	Salem	OR	4533	313	1352	15.26	23.5	92.3	82.2	0.0906	4.9	1.0	5.6	5.6	3.4	3.9	0.20
4A	Philadelphia	PA	4512	1332	1469	9.68	13.8	93.4	133.4	0.1189	4.5	5.4	6.1	6.7	3.7	4.7	0.19
5A	Pittsburgh	PA	5583	782	1392	1.04	5.2	89.7	125	0.1189	5.4	3.1	6.6	5.9	4.0	4.2	0.16
6A	Montreal	QC	7885	470	1352	-9.22	-9.8	86.1	114.5	0.0679	7.6	1.8	7.7	5.4	4.6	3.7	0.14

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7	Quebec	QC	9104	238	1299	-15.88	-14.9	84	111.5	0.0679	8.6	1.0	7.8	5.1	4.7	3.6	0.13
5A	Providence	RI	5562	743	1390	8.6	8.5	90.1	126.5	0.1304	5.3	3.0	6.3	6.0	3.8	4.2	0.18
3A	Charleston	SC	1880	2357	1676	25.7	27.3	94.3	150	0.1093	2.1	10.5	5.7	7.5	3.4	5.2	0.26
6A	Rapid City	SC	7000	671	1539	-13.36	-9.2	97.2	109.5	0.0896	6.4	2.3	7.6	6.6	4.6	4.6	0.13
6A	Huron	SD	7604	757	1493	-20.6	-14.6	94.1	132.2	0.0896	6.9	3.2	7.9	6.5	4.7	4.6	0.12
6A	Pierre	SD	7109	899	1494	-27.6	-11	98.9	123.2	0.0896	6.5	3.4	7.7	7.0	4.6	4.9	0.11
6A	Watertown	SD	8377	534	1291	-29.7	-15.6	90	129.5	0.0896	7.9	2.3	7.8	5.9	4.7	4.2	0.11
4A	Knoxville	TN	3594	1514	1565	11.12	16.5	93	131.5	0.0946	3.7	6.0	6.3	6.7	3.8	4.7	0.19
3A	Memphis	TN	2898	2253	1640	14.72	18.7	96.7	141.9	0.0946	3.1	9.5	6.3	7.7	3.8	5.4	0.20
4A	Nashville	TN	3518	1729	1577	10.4	14.8	94.8	135	0.0946	3.7	7.0	6.5	7.1	3.9	5.0	0.19
4B	Amarillo	TX	4102	1366	1817	9.5	9.8	97.3	114.9	0.1033	3.5	4.7	6.7	7.0	4.0	4.9	0.18
2A	Austin	TX	1671	2962	1667	26.42	26.6	99.8	141.9	0.1033	2.0	12.4	5.9	8.7	3.5	6.1	0.26
2A	Brownsville	TX	538	3986	1696	#N/A	38.1	95.4	152.2	0.1033	1.1	17.8	5.2	8.5	3.1	6.0	#N/A
3B	El Paso	TX	2383	2379	2065	28.76	23.9	100.7	114.3	0.1033	1.8	8.0	5.9	8.2	3.6	5.7	0.28
3A	Fort Worth	TX	2149	2785	1732	18.68	22	100.5	137.9	0.1033	2.3	11.3	6.1	8.7	3.7	6.1	0.22
2A	Houston	TX	1371	3059	1630	24.8	30.3	97.2	147.1	0.1033	1.9	13.3	5.6	8.3	3.4	5.8	0.25
2A	Port Arthur	TX	1356	2899	1654	28.76	31.4	94.5	153	0.1033	1.8	13.1	5.6	7.8	3.3	5.5	0.28
2A	San Antonio	TX	1418	3157	1800	25.16	29.2	99	139.9	0.1033	1.6	13.0	5.7	8.7	3.4	6.1	0.25

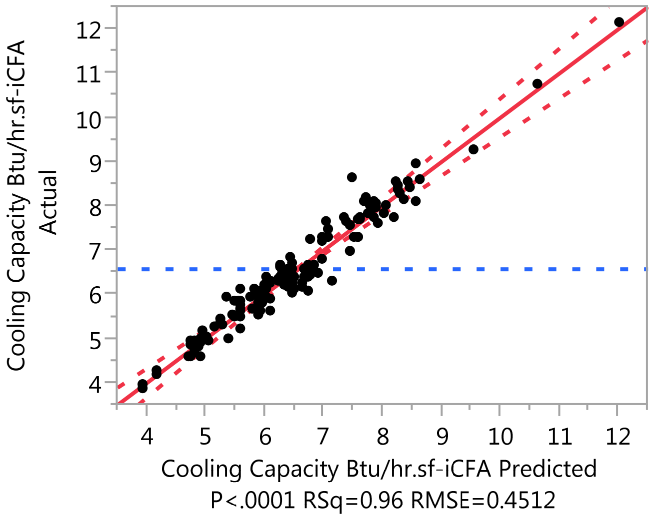
2A	Victoria	TX	1185	3193	1680	24.98	31	97.1	150.9	0.1033	1.7	14.2	5.6	8.4	3.4	5.9	0.25
5B	Salt Lake City	UT	5507	1218	1663	12.9	9.6	97.7	90.7	0.0893	5.0	3.2	6.5	6.7	3.9	4.7	0.20
4A	Charlottesville	VA	4211	1150	1421	9.32	16.4	93	126.6	0.1044	4.4	4.5	6.1	6.5	3.7	4.5	0.18
4A	Norfolk	VA	3230	1700	1545	21.38	22.5	93.7	139.2	0.1044	3.5	7.1	5.9	7.0	3.5	4.9	0.23
4A	Roanoke	VA	4044	1230	1542	15.44	15.7	92.3	125.3	0.1044	4.1	4.7	6.2	6.4	3.7	4.5	0.21
6A	Burlington	VT	7352	505	1340	-13.9	-7.8	88.4	117.1	0.1593	6.6	1.9	6.9	5.6	4.1	3.9	0.13
4C	Seattle	WA	4705	188	1240	21.2	25.2	85.3	81.4	0.0779	5.4	1.0	5.6	4.8	3.4	3.4	0.23
5B	Spokane	WA	6627	434	1410	4.1	4.7	92.8	77.3	0.0779	6.4	1.0	6.8	5.6	4.1	3.9	0.17
6A	Green Bay	WI	7599	479	1376	-15.34	-8.2	88.5	127.8	0.1181	7.0	2.1	7.2	5.8	4.3	4.0	0.13
6A	Madison	WI	7104	620	1426	-18.76	-7	89.6	130.4	0.1181	6.5	2.6	7.2	5.9	4.3	4.2	0.12
4A	Huntington	WV	4426	1156	1446	5.54	10.1	91.9	133.1	0.0915	4.6	4.7	6.7	6.4	4.0	4.5	0.17
6B	Casper	WY	7285	461	1577	-13.54	-8.3	93.8	85.9	0.0896	6.5	1.2	7.5	5.8	4.5	4.1	0.13
6B	Sheridan	WY	7392	454	1533	-9.4	-10.7	95.3	94.4	0.0896	6.7	1.3	7.7	6.1	4.6	4.2	0.14

10 Appendix D – Statistical modeling – example screening fit

Screening fit:

Response Cooling Capacity Btu/hr.sf-iCFA

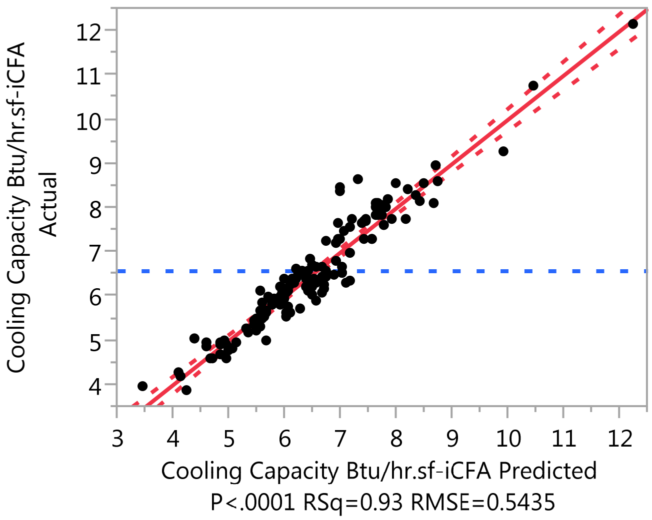
Actual by Predicted Plot



Term	Orthog Estimate
CDD65 F.days	1.143082
Cooling design dry bulb temp 0.4% [F]	0.557223
Global solar radiation kWh/m2.yr	0.253527
(CDD65 F.days-1375.71)*(Cooling design dry bulb temp 0.4% [F]-92.3865)	0.219619
(CDD65 F.days-1375.71)*(Global solar radiation kWh/m2.yr-1546.77)	0.157075
(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)*(Electricity price $/kWh-0.11085)	-0.105346
(CDD65 F.days-1375.71)*(Electricity price $/kWh-0.11085)	-0.094008
(Global solar radiation kWh/m2.yr-1546.77)*(Electricity price $/kWh-0.11085)	0.079029
(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	0.075657
Electricity price $/kWh	-0.072785
(Global solar radiation kWh/m2.yr-1546.77)*(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	-0.068578
Dehumidification design humidity ratio 0.4% [grains/lb]	0.067497
(Electricity price $/kWh-0.11085)*(Electricity price $/kWh-0.11085)	-0.058085
(CDD65 F.days-1375.71)*(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Electricity price $/kWh-0.11085)	-0.056978
(CDD65 F.days-1375.71)*(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	-0.046436
(Global solar radiation kWh/m2.yr-1546.77)*(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Electricity price $/kWh-0.11085)	0.045456
(Global solar radiation kWh/m2.yr-1546.77)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)*(Electricity price $/kWh-0.11085)	-0.037982
(Global solar radiation kWh/m2.yr-1546.77)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	0.034166
(Global solar radiation kWh/m2.yr-1546.77)*(Cooling design dry bulb temp 0.4% [F]-92.3865)	0.031651
(CDD65 F.days-1375.71)*(CDD65 F.days-1375.71)	-0.030917
(CDD65 F.days-1375.71)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	0.021293
(Global solar radiation kWh/m2.yr-1546.77)*(Global solar radiation kWh/m2.yr-1546.77)	0.019665
(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)*(Electricity price $/kWh-0.11085)	0.017696
(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Cooling design dry bulb temp 0.4% [F]-92.3865)	0.013533
(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Electricity price $/kWh-0.11085)	0.013532
(CDD65 F.days-1375.71)*(Global solar radiation kWh/m2.yr-1546.77)*(Electricity price $/kWh-0.11085)	0.010424
(CDD65 F.days-1375.71)*(Global solar radiation kWh/m2.yr-1546.77)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	0.008685
(CDD65 F.days-1375.71)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)*(Electricity price $/kWh-0.11085)	0.007020
(CDD65 F.days-1375.71)*(Global solar radiation kWh/m2.yr-1546.77)*(Cooling design dry bulb temp 0.4% [F]-92.3865)	0.003114
(Cooling design dry bulb temp 0.4% [F]-92.3865)*(Dehumidification design humidity ratio 0.4% [grains/lb]-120.043)	0.000831

Final fit:

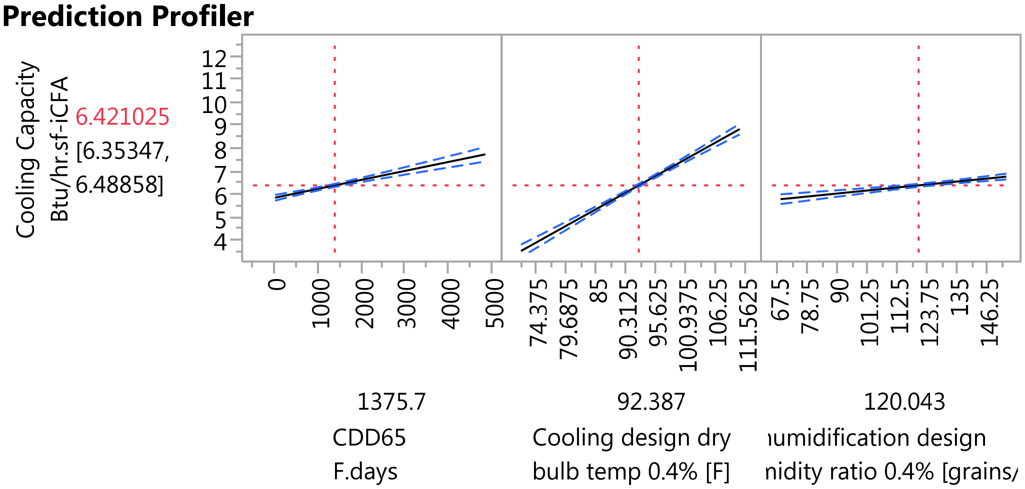
The R-squared and RMS error are almost as good, and the model is a lot simpler.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	t Ratio	Prob>|t|
Cooling design dry bulb temp 0.4% [F]	0.1365094	0.006333	21.56		<.0001*
(Cooling design dry bulb temp 0.4% [F]-92.3865)*(CDD65 F.days-1375.71)	3.6453e-5	3.966e-6	9.19		<.0001*
CDD65 F.days	0.0003903	0.000043	9.08		<.0001*
Dehumidification design humidity ratio 0.4% [grains/lb]	0.0115813	0.001847	6.27		<.0001*

Prediction Profiler



11 Appendix E – PHIUS Technical Committee members

For their many and significant contributions to this study, the authors thank the members of the PHIUS Technical Committee:

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Stuart Fix

Achilles Karagiozis

Katrin Klingenberg

Russell Richman

John Semmelhack

Jesse Thomas

Graham Wright

12 Appendix F – Passive measures and strategies

This list is from the charter of the nascent Global Passive Building Council.

Building site selection and orientation

Building size, shape, spacing

Thermal mass (as appropriate)

Solar protection and shading, e.g. vegetation, roof overhangs

Daylighting design, window placement, selection of glazing properties

Passive solar gains (in moderation)

Coupling to the earth (as appropriate)

Ventilation (natural or mechanical, with heat-and-moisture recovery as appropriate)

Night flush ventilation as appropriate (i.e. wide daily outside temperature swing)

Evaporative cooling as appropriate (i.e. hot dry climates)

Air-sealing, air-tight construction

Continuous insulation, connection details free of thermal bridges

Safe handling of air for combustion

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This report was prepared with the cooperation of the U.S. Department of Energy's Building America Program.

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Betsy Pettit, FAIA, is the president of Building Science Corporation and is a registered architect with over 30 years of professional experience. She is currently the project manager for Building Science Corporation's Building America project that has provided whole system designs for over 3,000 high performance houses nationwide.

Graham S. Wright leads PHIUS' research and development efforts, including ongoing work to adapt the existing passive house standard to North American climate zones. He also established and leads the PHIUS Certified Data for Windows program, which evaluates windows for use in passive building applications for specific climate zones. Wright also helped launch the PHIUS+ Certification program, and still provides input to that program.

Katrin Klingenberg, PHIUS Co-Founder and executive director, built the very first home built in the United States to the Passive House standard in 2003. Her experience led to her founding e-cological Construction Laboratory (e-colab) to further investigate applying passive building principles in the United States. Working partnership with the City of Urbana, e-colab became a Community Home Development Organization (CHDO) and built single-family passive house projects as affordable housing units.

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