NET ZERO RESIDENTIAL: FEASIBILTY AND MICROCLIMATE RESPONSIVE DESIGN FOR A COLD CLIMATE

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STATEMENT OF PURPOSE

The purpose of this paper is to demonstrate the use of simulation in designing cost efficient Net-Zero homes for cold climates.

ABSTRACT

Technology available today enables us to design and build Net-Zero homes—where all of the necessary heating, cooling, hot water, and electricity are produced on-site. A major challenge with Net-Zero design has been the appropriate sizing of the systems, due in part to the large differences in microclimates between locations which might otherwise appear to be very similar. As an example, multiple locations in the same AHSRAE or Energy Star climate zones often have significantly different local conditions for temperature, humidity, wind direction and speed, and solar availability. Another challenge with Net-Zero design is the uncertainty of performance and cost effectiveness of different strategies, particularly in comparing passive strategies vs. active systems.

This paper is part of an extensive project focusing on residential design and construction where solar design and Passivhaus strategies are utilized to achieve Net-Zero energy-use. The focus of this paper is to highlight the differences in optimal architectural and mechanical system design strategies for three locations along the Rocky Mountain front range including: Denver, CO, Billings, MT, and Laramie, WY. These three locations reveal small differences in temperature, wind speed, and solar availability, but enough to create very different constraints for energy demand and availability, resulting in a variety of climate specific, cost effective design solutions.

1. INTRODUCTION

The motivation behind the research is to develop prototype Net-Zero home designs that are constructible, desirable, and affordable. Each location presents unique constraints in terms of air temperature, wind, and solar availability, so it has been clear from the onset that each location would have a custom solution. The microclimate challenges associated with a Net-Zero goal requires that the design process emphasis simulation, where energy and first costs can be evaluated side by side.

This paper documents our design and simulation methodology, exposing both opportunities and limitations for active mechanical systems and passive technologies. Our conclusions will indicate significant opportunities in the US to design cost efficient Net-Zero homes using simulation and economic analysis for market based solutions. This process, we argue, can and should be followed by designers and home builders.

1.1 Initial House Layout

Our design objective is to create the highest performing home that is still both affordable and attractive. In designing a house that meets both objectives, we decided to find, rather than produce, an acceptable design. We considered Net-Zero precedent homes before reviewing countless generic home plans, specifically looking for a traditional appearance that could achieve a high degree of energy efficiency. We searched for designs based on the following criteria:

1) Simple form without excessive corners or roof-lines.
2) Compact form that can flexibly fit on an urban lot.
3) A high volume/surface area ratio to reduce heat loss.
4) A relatively large solar envelope.
5) 3-4 bedrooms design that efficiently utilizes space.

With these as our objectives, we settled on a simple two story rectangular house with 3 bedrooms, 2.5 baths, an office, and without a basement or garage. This scheme shown in figure 1, takes cues from other successful Net-Zero designs (Goodman 2011), and although it is not necessarily a final design it provides a starting point for our analysis.

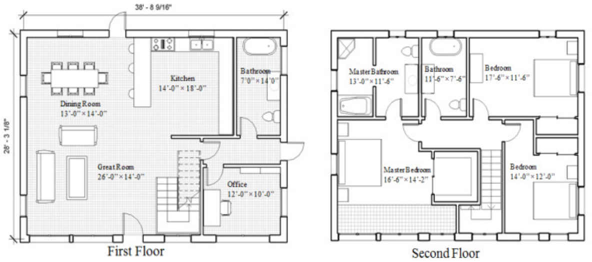


Figure 1: Initial House Design (Floor Plans).

1.2 Net-Zero Strategy

While there may not be a unique definition of Net-Zero Energy, we must choose a specific definition for our project. Torcellini et al. (2006) defines ZEB (Zero Energy Building) as "the idea that buildings can meet all their energy requirements from low-cost, locally available, nonpolluting, renewable sources. At the strictest level, a ZEB generates enough renewable energy on site to equal or exceed its annual energy use." To meet Net-Zero we use the strictest definition, with a goal of on-site energy generation that matches annual consumption. In achieving Net-Zero, it is important to first reduce the energy demands, then meet the reduced needs with on-site energy production (Zaretsky, 2010). The extent that we should favor passive strategies before considering active ones is an important question we intend to explore.

On-site energy generation commonly occurs in two forms: wind and solar. Both wind and solar are expensive relative to residential construction costs, so reducing the energy demand and thus the required production is much desired.

1.3 Reducing Loads with Passive Strategies

The three locations evaluated for this study fall within the coldest (Northern) Energy Star climate zone (figure 2), which is particularly relevant for energy efficient window specifications (Efficient Windows Collaborative 2012). Considering temperature differences, Denver has 6380 heating degree-days; Billings has 6770; and Laramie has 9140.

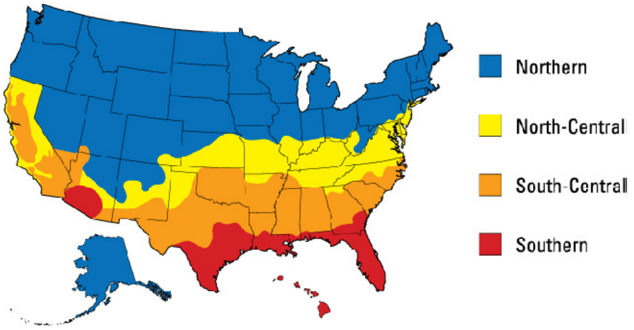


Fig. 2: Energy Star climate zones.

As mentioned, our first goal for Net-Zero is to reduce energy demand, the balance of which must be produced through renewable systems. Our goal also includes lowering first costs, and in the effort to decrease loads we expect at some point that the cost/benefit of passive strategies is out-weighed by active systems. For example, we can maximize our south glazing using high performance windows that enable us to capture and store enough direct solar energy for the coldest winter days, but it will be cheaper at some point to invest more in active systems, where energy is produced year-round.

Evaluating first costs can be problematic in early design. Price quotes for materials, equipment, and labor, can vary by 200 percent or more for a single product or technology. For our study, we are using what we believe to be typical costs, but it must be understood that costs will vary, and can change over time as new technologies emerge and mature.

2. METHODOLOGY

2.1 Simulation Strategy Overview

To explore the most cost effective path to Net-Zero, this research pursued the following steps:

1) Determine envelope properties to be evaluated.
2) Simulate heating loads for various wall-to-window ratios for south windows, evaluating multiple glazing and wall types.

3) Determine average electricity use.
4) Simulate solar availability by location.
5) Determine wind availability by location.
6) Develop a cost matrix for various construction types and systems.
7) Assuming grid-tie to a smart grid, create economic analysis for reaching Net-Zero with a focus on heating strategies.

Having completed these steps, a designer or builder can find an economic balance between passive and active strategies.

2.2 Simulation Tools

We have chosen three software tools that fit our current needs: Autodesk Vasari, Autodesk Ecotect 2010, and Design Builder 3.0. Vasari, based on the Autodesk Revit modeling interface, is a free program in development that specifically supports conceptual design and analysis. Vasari has built in simulation capabilities, but we have chosen not to rely on functionality in development. Instead, we export our design model to the other analysis programs.

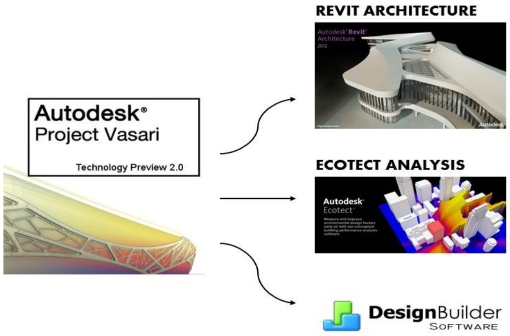


Fig. 3: Design and Simulation Software.

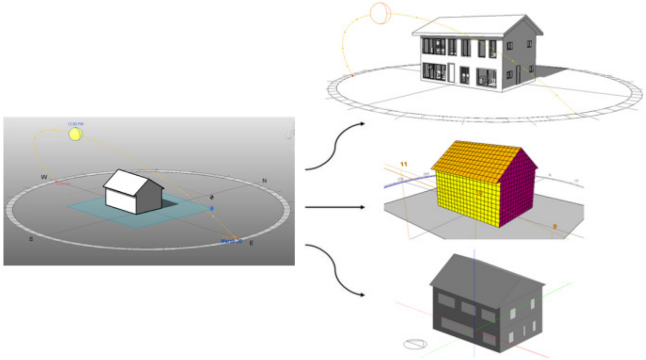


Fig. 4: Building Model in Vasari, Revit, Ecotect, and Design Builder.

2.3 Max and Min Values

When simulating a range of design values, industry targets need to be considered. We agree that loads must first be reduced before employing active strategies, so our simulated range of values started fairly high in terms of performance. Our worst-case simulation values came from the International Energy Conservation Code (IECC) 2012 residential standard, while our maximum values used the Passivhaus target for window U value, air infiltration, and super-insulated walls. (Passive House Institute 2004).

Highest Performance Values:

Window U Value	.14
Infiltration	.6ACH @ 50Pascals
Wall R Value	40
Roof R Value	60
Slab Insulation U Value	30

IECC 2012 Appx Values:

Window U Value	.32
Infiltration	3 ACH @ 50Pascals
Wall R Value	20
Roof R Value	60
Slab Insulation U Value	30

2.4 Heating

According to US Energy Information Administration's Residential Energy Consumption Survey (RECS 2005), natural gas energy use was more than double the electricity use for the average American home in a cold climate (5500+ HDD). Some of this usage can be attributed to water heating and other uses, but the majority goes towards space heating. Due to the dominance of heating in cold climates, the prime focus of our analysis process is to evaluate passive heating reduction strategies against active heating technologies in determining the lowest first cost for achieving Net-Zero.

Some passive technologies are relatively inexpensive, such as increased insulation, while others can be much more expensive. Determining the most economical approach to heating the house with on-site energy generation is our primary concern.

2.5 Electricity Generation

Regardless of the design, all homes use a considerable amount of electricity for electronics, appliance, etc. To create a Net-Zero house, this usage must be offset by on-site renewable sources. Considering the bigger picture in terms of energy production, the purchasing of off-site wind or solar equipment is probably more cost-effective than on-site generation, however there are significant benefits to on-site solutions: 1) user accountability for energy usage, 2) user reductions based on site availability constraints, 3) land-use ethics with increasing global populations. In response to these and other concerns there is an emerging market for Net Zero homes (NAHB Research 2006). While the first cost of Net-Zero may or may not be economically beneficial in terms of energy cost savings, the goal is recognized as an achievable mean of conserving energy resources and reducing our carbon footprint (NAHB Research 2006).

Both grid-tied and off-grid solutions are relevant, particularly considering the resources and infrastructure necessary for rural developments to connect to the grid. Our research will eventually compare both options, however, this paper examines only a grid-tied condition.

We determined the electricity generation required for our house based on the US average for cold climates, which we then reduced based on our square footage. From RECS we found the US average to be about 33000 kBtu with the average home size close to 2400 sf. Considering our size of 2100 sf, we reduced our target to 30,000 kBtu.

2.6 Wind vs. Solar

Our analysis includes an evaluation of both solar and wind power, however it focuses on solar as the more feasible option due to wind siting and permitting issues.

2.7 Cooling

Early energy simulations which included window shading and ventilation revealed that cooling could be removed altogether due to the large summer temperature swing between day and night in our locations. It should be noted that the US average data includes cooling electricity use, so it is reasonable to assume that our electricity generation will provide enough power for any cooling needs.

2.8 Domestic Hot Water

Hot water for Net-Zero homes is most efficiently heated with solar thermal applications; however the challenge lies in sizing the system appropriately. Hot water energy usage is assumed to be consistent across the seasons since the occupancy does not change nor does the temperature of the incoming water. Sizing the system to meet the worst case demand with solar hot water will produce excess heat in the summer, so it is advisable to size the system below the worst case capacity, and make up the different with an alternate energy source (Brown et. all, 2000). Since we are making the assumption that solar hot water is the most efficient system, a cost benefit analysis is not necessary, however our design needs to account for solar thermal panels taking up space on our roof.

3. CLIMATE COMPARISON

A careful evaluation of the three locations reveals significant differences in temperature, solar, and wind availability.

3.1 Heating and Cooling Degree Days

The US department of Housing and Urban Development (HUD) web page provides a database of heating and cooling degree days for US cities. Table 1 show heating and cooling degree days taken from an average of two weather stations for each location. Using Denver as the basis for comparison, Billings has shows a similar amount of heating degree days while Laramie is significantly colder with 43% more heating degree days. In all climates, cooling degree days are far fewer, ranging between 1 - 9% of the heating degree days. Laramie shows still significantly fewer cooling degree days, while Denver and Billings are closer with Billings being slighter warmer overall.

TABLE 1: HEATING/COOLING DEGREE DAYS

Location	Heating DD	% Change
Denver	6381	0%
Laramie	9136	43%
Billings	6767	6%

Location	Cooling DD	% Change
Denver	466	0%
Laramie	73	-84%
Billings	621	33%

3.1 Solar Availability

In evaluating solar availability it is important to consider surface insolation, or the amount of incident solar radiation received on a given roof angle and orientation. For consistency between locations we used a roof slope of 35% off of the horizon, facing due south. Each location has a different optimal slope and orientation, however we chose a consistent roof based on a combination of optimal values and practicality in terms of siting and constructability. Our chosen roof angle would receive very close to the optimal insolation values. For example, the optimal solar radiation in Laramie is received on a surface facing 18 degrees from south towards the east, and 33 degrees off of the horizon, while the optimal winter angle is 59 degrees off of the horizon and 10 degrees towards the east. Yet, the difference in solar radiation between these and our chosen surface is less than 2% for each case, as is shown in tables 2 and 3.

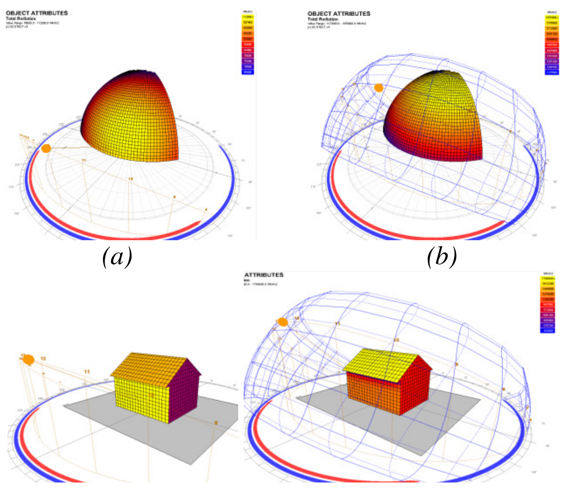
TABLE 2: SOLAR AVAILABILITY IN LARAMIE PER YEAR

Tilt	Orientation	Solar availability (kbtu/ft^2)
35°	180°	579.5
33°	162°	589 (max angle)

TABLE 3 SOLAR AVAILABILITY IN LARAMIE DEC 07- JAN 06

Tilt	Orientation	Solar availability (kbtu/ft^2)
35°	180°	30.8
59°	170°	31.2 (max angle)

Our data comes from solar simulations where we compared our building shape to a sphere—where the solar values for any angle and orientation can be found (figure 5).


(a) *(b)*

(c) *(d)*

Fig. 5: (a) Sphere Analysis Dec 07 – Jan 06; (b) Annual Sphere Analysis (c) Solar Radiation Analysis Dec 07 – Jan 06; (d) Annual Solar Radiation Analysis in Laramie, by Autodesk Ecotect.

A slightly more noticeable difference was seen in winter solar gains for Denver and Billings where the optimal angle and orientation saw a 10-15% increase in solar gain. This is relevant for reducing winter heating loads with direct solar gains, however our energy simulations with slightly rotated buildings showed only marginal improvements.

Overall, the annual solar availability on our roofs was fairly similar between locations, with a noticeable reduction in Billings at -11% (Table 4). Winter solar availability showed significant differences with Laramie at -14% and Billings at -35% from Denver (Table 5).

TABLE 4: ANNUAL SOLAR INSOLATION BASED ON PREFERRED TILT AND ORIENTATION (35, 180)

Location	Annual Insolation (kBtu/ft^2)	Percent change
Denver	585	0
Laramie	580	-1%
Billings	528	-11%

TABLE 5: DECEMBER SOLAR INSOLATION BASED ON PREFERRED TILT AND ORIENTATION (35, 180)

Location	December Insolation (kbtu/ft2)	Percent change
Denver	35	0
Laramie	30.8	-14%
Billings	26	-35%

To evaluate the amount of solar heat entering the space, we referred to our energy simulation model to compare the direct gain during the worst four months of winter, November through February. Denver showed significantly higher solar gains across this season, with Laramie and Billings at -16% and -49% respectively (Table 6).

TABLE 6: DIRECT SOLAR GAINS IN WINTER MONTHS (NOVEMBER THROUGH FEBRUARY)

Location	Winter solar gain (kbtu)	Percent change
Denver	13334	0
Laramie	11542	-16%
Billings	8933	-49%

3.2 Wind Availability

Evaluating wind speed for wind power potential is less straightforward than solar since the general formula for wind power relies on the cube of the wind speed (V in the equation below).

$$P = \frac{1}{2}\rho\pi r^2 f_p V^3$$

The impact of this is seen when the average speeds are cubed, where wind speeds that appear to be similar result in drastically different values for wind power. The increase in wind power potential, again using Denver as the base, is +200% for Billings and +292% for Laramie (Table 10).

TABLE 10: AVERAGE ANNUAL WIND SPEED AND WIND POWER POTENTIAL

Location	Average Wind Speed	Wind Speed Cubed	Percent Change
Denver	14.1	2815	0
Laramie	20.2	8222	292%
Billings	17.8	5634	200%

The impacts of these climate differences on energy savings and production strategies will be evaluated through both energy simulations and cost comparisons.

4. WIND VS SOLAR COMPARISON

Our evaluation of on-site energy production considers both wind and solar. Choosing the appropriate system becomes increasingly complex at the residential scale. Both systems are plagued with siting and maintenance issues and both systems can be rejected by home owners associations, however wind turbines are much more prone to these issues. The major setback for wind towers in urban areas is usually height restrictions. Even when a permit can be obtained, it is difficult to find a site location with constant wind, unaffected by buildings, trees, or terrain. For these and other reasons, the most common applications for small-scale wind turbines are in rural areas (U.S.D.O.E.).

For a cost evaluation of solar vs wind, we used a minimum electricity requirement of 30,000+ kBtus. We calculated solar power based on 15% efficiency using our simulated values for each location, but for wind we used the manufacturer power production data based on average wind speed. Cost data for solar systems was more consistent than wind (tables 11 and 12) due to a wide price range, yet for all products and locations wind power could be more cost effective, particularly in Billings and Laramie where wind could produce 150 to 200% of the same energy as a PV system of the same price. While the reality of residential wind power in cities has many limitations, the potential is very good, particularly in locations with high wind speeds.

TABLE 12: SOLAR INSTALLATION EVALUATION FOR 30,000KBTU ANNUAL PRODUCTION

Location	PV System A	PV System B
Denver	$22,000.00	$26,400.00
Laramie	$22,000.00	$26,400.00
Billings	$24,000.00	$28,800.00

TABLE 11: WIND TURBINE EVALUATION

Location	Wind Turbine A (35–60 ft tower)	Wind Turbine B (70 ft Tower)
Cost Including Installation	$8,000 - $20,000	$15,000 - $20,000
Yearly Production Denver (kBtu)	20,500	30,700
Yearly Production Laramie (kBtu)	31,500	57,300
Yearly Production Billings (kBtu)	27,800	45,000

While it appears that wind power would be the optimal solution for at least two of our locations, we've chosen to focus the remainder of our analysis on solar systems which are more easily incorporated into urban residential sites.

5. HEATING LOADS COMPARISON

We evaluated a range of design and construction data to determine the most cost effective methods for reducing loads passively before addressing theses loads with active strategies. Our simulated input value includes a range of variables based on the approximate differences between the Passivhaus standard and IECC 2012 (table 13). We also simulated various wall to window ratios for the south wall.

TABLE 13: HEATING LOAD SIMULATION PROPERTIES

Wall R Value		40, 35, 30, 25, 20
Windows	U Value	.138, .201, .264, .328
	SHGC	.47, .467, .564, .687
Infiltration (ACH):		.12, .25
South Wall to Window %		20, 30, 40, 50, 60

Our simulations produced 200 results per location which we evaluated against cost data. While investigating methods of data evaluation, we conducted early cost analysis considering the best and worst cases for each climate, along with max and min values found by modifying a single variable (table 14). Our results indicated that Denver has the lowest heating loads in all cases, followed by Laramie which is a surprise when comparing it's heating degree days to Billings. The variables with the greatest impact on heating were similar for all locations: the south window to wall ratio had the single biggest impact, followed by both infiltration and wall R value which had comparable impacts. Changes to window U value did not show as great of an impact, and upon closer inspection the U value was at times less influential than Solar Heat Gain Coefficient (SHGC).

TABLE 14: HEATING LOAD SIMULATION RESULTS

	Denver kBtu	Laramie kBtu	Billings kBtu
Worst (IECC 2012)	8179	12191	13329
Window/Wall = 60%	3051	4920	7356
Wall R = 40	4686	7536	9246
Window U = .138	6528	9954	11424
ACH = .12	4836	8049	9084
Best (Combined)	528	937	2022

6. HEATING COST COMPARISON

6.1 Walls and Windows

To make practical use of our solar PV and heating analysis, we found cost data associated with changes to our wall and window design. Finding consistent cost data is problematic due to the nature of industry sales, but we found windows to be most challenging for a couple of reasons: 1) what you pay is often determined by distributor mark-up, 2) windows are visible architectural features whose costs are also influenced by materials and finished appearance. We had to take an average of data we found, and chose to leave out the lowest cost windows made of vinyl because they could be rejected by homeowners due to appearance, durability, etc.

With walls we first compared standard stick-built systems against SIPs (structural insulated panels). SIPs require simple shapes, such as ours, and often cost less in terms of labor and materials. However, SIPs can end up costing considerably more once you account for the heavy machinery required during installation. In an effort to avoid a potentially flawed cost analysis, we considered only SIP wall types, comparing thicknesses of SIPs using cost estimating data from R.S. Means (R. S. Means 2012)

A cost assessment of infiltration would be even more problematic, as air infiltration is determined by a combination of wall types, window types, and best practice detailing around corners and openings. For this reason we did not conduct cost analysis related to infiltration, however it should be noted that a super tight house (below .25 ACH) will require a ventilation system with heat recover – not included in our simulations.

Our research shows that our greatest cost accompanied our least effective passive measure – window performance. An improvement in wall R value was the least expensive strategy, yet was fairly effective. The biggest "bang for the buck" came with an increased wall to window ratio on the south wall, but only when assuming the least expensive of our window options.

TABLE 15: WALL AND WINDOW COSTS WITH LARAMIE HEATING LOADS

	Additional Cost	Laramie kBtu
Worst (IECC 2012)	$0	12191
Window/Wall = 60%	$7,830	4920
Wall R = 40	$5,120	7536
Window U = .138	$19,880	9954
ACH = .12	?	8049
Combined	$70,150	937

6.2 Heating Systems

Evaluating active heating systems, we first had to make a comparison between solar thermal heat and electricity. For our hot water system we would already be installing solar thermal panels on the roof, therefore it made sense to tie into that system for space heating. However, when sizing the system to supply the peak winter heating with low levels of winter solar availability, we found that equipment size and costs could quickly escalate. Not only is solar thermal more expensive, but overall it is much less efficient considering productivity only in winter. Comparing solar thermal systems against a PV powered heat pump, we soon discovered that heat pumps are much more efficient and economical for grid-tied Net-Zero homes. There are a couple reasons for this conclusion:

1) Solar thermal systems convert 30 – 40 % of solar energy into heat that is delivered to the space. PVs convert 15% of solar energy into electricity, and with a heat pump with a coefficient of performance (COP) of over 2, the two systems function at nearly the same efficiency. Current air-to-air heat pumps for cold climates are being produced with a COP above 3, while ground source heat pumps are up to 5.

2) Solar energy is collected year round with PVs. With a manageable heating load, a heat pump can be running at its lowest efficiency (COP 1) and still use less energy during winter than small area of PVs can produce annually. With a grid tie and annual solar production, including production during the summer peak months, the required area and cost of PVs was drastically lower than solar thermal heating systems.

We considered an unspecified heat pump with a COP of 2.5., and chose not to add first costs for the heat pump since this could be comparable to a standard heating system (heat pumps also cool in the summer to offset potential AC equipment costs). Our heat pump analysis revealed that the worst performing house in terms of passive strategies could reach Net Zero with about 4 additional PVs, at an additional cost of around $4000. Comparing passive strategy costs savings against the cost of additional PV production, it is clear that passive strategies become less cost effective in the realm of super-high performance (Table 16).

TABLE 16: WALL AND WINDOW COSTS, LARAMIE HEATING LOADS, ADDITIONAL PV COSTS TO REACH NET ZERO

	Additional Cost	Laramie kBtu	Additional PV Cost
Worst (IECC 2012)	$0	12191	$4,000
Wind./Wall = 60%	$7,830	4920	$2,000
Wall R = 40	$5,120	7536	$3,000
Window U = .138	$19,880	9954	$3,000
ACH = .12	?	8049	$3,000
Best (Combined)	$49,530	937	$1,000

6.3 Required Roof Area

Available roof space for PV and solar thermal systems can always be a limiting factor. Denver, with the highest solar availability for PV production, had enough roof space to reach Net-Zero. Laramie required a small extension to the south overhang while Billings required either a form change or a separate structure for more PVs. At an early stage, the design can adapt with little cost repercussions, while later these challenges might potentially jeopardize a Net-Zero effort.

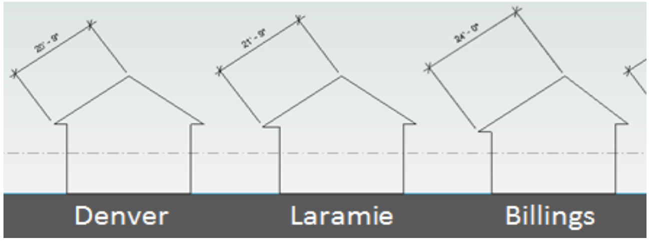


Fig. 5: Required roof area for each location.

7. DISCUSSION

We began our research with the intent of designing three Net- Zero homes in related climates (Denver, Laramie, and Billings) focusing on the subtle climate differences that could have a major impact on performance. Immediately we discovered that wind power has better economic potential than solar, where even a moderate increase in wind speed can have a huge impact on energy production. However, due to concerns for siting and permitting, we directed our focus towards solar. Annual solar availability is similar for our climates, while Denver has noticeably higher winter availability with Laramie somewhere between Denver and Billings. Outdoor air temperature, measured by heating and cooling degree days, is similar between Denver and Billings while Laramie is much colder.

We designed a schematic home that follows good passive design principals while allowing adequate roof space for solar thermal and PV panels. We compared the annual heating requirements through energy simulations where we modified window, wall, and envelope performance values from IECC 2012 as our minimum to Passivhaus standards and recommendations. Our house in Denver performed better in all simulations, evident that solar heating plays a major role in reducing the winter loads. Laramie, while much colder than Billings, still required less annual heating which we again attribute to direct solar gain. Had we simply relied on passive strategies with a goal of saving energy, we would find that the three climates have very different heating needs. Using the IECC minimum values, Denver performed the best while Laramie and Billings both required approximately 50% more heating. With higher performing window and wall configurations, Denver heating loads dropped very low while Laramie and Billings had two and four times the heating requirements respectively.

We compared our simulation input values against material and constructions costs, looking for a balance between efficiency and economics. Our evaluation of the cost benefit of passive strategies was somewhat irrelevant once we compared active strategies and their first costs to reach Net-Zero. Our belief that the path to Net-Zero must start with load reductions proved to be somewhat misleading. The reason for this, we believe, is that our worst simulation variables (IECC 2012) are actually fairly high—even with the IECC minimums, our designs performed significantly better then the US cold climate average. We then found that a limiting factor might not even be costs, but the availability of roof area, supporting our case for early design simulation.

The current generation of simulation tools permits a more sophisticated evaluation of design options than ever before. This paper concludes that active systems are significantly more cost effective than super-high performance passive measures to meet Net-Zero in the Rocky Mountain region. Once an effort is made to meet a minimum standard such as IECC 2012, a designer should move to active systems as the most efficient path to Net-Zero for grid-tied projects.

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