

PASSIVE SOLAR GREENHOUSES

A do-it-yourself Design Guide

SECOND EDITION


ROB AVIS, P.ENG

VERGE PERMACULTURE

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CONTENTS

1 INTRODUCTION

3 GETTING STARTED

Rules of thumb — 3

Resources — 4

Mistakes I made — 4

5 GOALS

Example: greenhouse cannot freeze — 5

Example: greenhouse can freeze — 6

Minimum temperatures — 6

8 SITE SELECTION, ORIENTATION & ASPECT

Shading and solar access — 8

Orientation — 9

Slope — 10

Aspect ratio and height — 10

12 BUILDING SHAPE

Angled glazing — 12

Knee wall and ventilation louvres — 13

Small greenhouse — 14

Large greenhouse — 17

20 FOUNDATIONS AND SOIL

Alternative foundations — 21

The importance of soil — 22

24 VENTILATION
Moving air — 24
Adjusting temperatures — 25
Vestibules and breakout doors — 27
Condensation — 28
Attaching a greenhouse to existing structures — 28

30 GLAZING & LIGHT
Transmissivity — 30
Polycarbonate — 31
Light — 32
Reflective walls — 32

34 THERMAL MASS
Storing heat with water — 35
Storing heat with cob and rock — 36
Storing heat with soil and plants — 37

38 INSULATION
Insulated Blinds — 39
Low Cost Insulation Material — 41

43 HEAT LOAD ANALYSIS
Heat loss — 43
Calculations — 43
Extreme temperatures and heating degree days — 44
Heat loss worksheet — 45
An example: Benefits of a thermal curtain — 47

50 HEATERS AND INTEGRATED DESIGN
Rocket Mass Heater — 51
Subterranean Heating and Cooling Systems — 51
Integrated Design — 52

54 A FINAL WORD
About the author — 55
Acknowledgements — 56

INTRODUCTION

The interplay between thermodynamics and biology has fascinated me for as long as I can remember, and passive solar greenhouses—greenhouses that heat and cool themselves without additional gadgets or energy—perfectly intersect these two realms of science.

I've been fortunate to experiment with one I designed and built in the fall of 2010, and since then I've learned a great deal about what does and doesn't work. The process of discovery continues each year as I make new mistakes, learn innovative ways to grow in a controlled environment, and gain new insights into how I could have designed it better.

This book documents lessons learned from my own research, experimentation, and background as an engineer, plus insights gleaned from authors such as Shane Smith and James McCullagh, and true pioneers like Jerome Osentowski of the Central Rocky Mountain Permaculture Institute in Colorado.

Early on I recognized a fundamental challenge for home greenhouse projects: plants prefer to live outdoors. It might seem strange to tell you this just as you begin to read about how to make a greenhouse, but we just can't beat natural systems. Greenhouses separate plants from the external environment, and so create ecological pressures that wouldn't exist outdoors in the fresh air, sun, wind, and rain. As such, we end up having more issues with insects and diseases than you might expect in an outdoor garden.

So why do I keep at it? In short, to grow more food—and more diverse food—in my harsh climate. My bioregion only has 100 frost-free days, but my greenhouse more than doubles that, up to 250 frost-free days. I'm close to the mountains that slow down outdoor plants with cold nights and winds, but in my greenhouse tomatoes are ripe by mid-summer. I also live in one of the most aggressive hail belts in the world, where frequent storms threaten unprotected crops with devastation.

Other reasons are just as important, and I truly believe that the benefits of the greenhouse extend far beyond the glazing. Designed properly, passive solar greenhouses are extremely productive, fun, and healthy places. They offer year-round learning opportunities and, when I need a quiet moment, my greenhouse offers a sanctuary.


My greenhouse

Increasing evidence points to a failing industrial food system, so it has become more important than ever to control our own food supply. As we grow our food—and lots of it—we gain that control and empower ourselves, starting right in our backyards.

I hope you enjoy this e-book and keep an eye on our website for updates on our urban greenhouse and many other projects.

GETTING STARTED

This book is organized into ten chapters that each identify important design considerations and rules of thumb that will get you most of the way to designing your own passive solar greenhouse.

We begin with different goals for your greenhouse that will directly impact all your subsequent design decisions, beginning with site selection, including orientation and aspect, and building shape. From there we discuss options for foundations, ventilation, glazing, and getting the most light for your plants.

In the final chapters we move into the core of passive solar greenhouses, including choices for thermal mass and insulation. We cover the basics of heat load analysis to give you a better idea of how your greenhouse will perform and to help you size heaters. We cover some heating options in the final chapter along with possibilities for integrated designs that promise to increase the efficiency and productivity of your greenhouse.

Throughout the text I've clearly highlighted rules of thumb, resources, and short anecdotes about mistakes I've made.

Rules of thumb

Although not strictly accurate in every situation, the rules of thumb I present are broadly applicable principles that will help you make approximate calculations as your design develops.

I don't advise that you rely entirely on these rules of thumb. To complete your design, I strongly suggest additional reading and, in some cases, a professional engineer.

Resources

At the end of each chapter I list books, blogs, and other resources that I have found to be helpful. If you are reading this on your computer, you can use the "Contents", "List of Figures", and "List of Tables" to navigate quickly around the book. For online readers, links to websites are provided.

If you need guidance beyond what you find here, we regularly provide consultations on greenhouses and other design topics, so please don't hesitate to contact us.

Mistakes I made

I've been sure to highlight mistakes I've made and things I would do differently if I were to do them again. In fact, I plan to retrofit my greenhouse soon, so keep an eye open for future developments.

A NOTE ABOUT UNITS

As an engineer I prefer metric units—degrees Celcius (°C), metres (m), kilograms (kg), watts (W), and the like—but imperial units remain standard in the North American building industry and, like most Canadians, I use both!

For building dimensions I use feet instead of meters: 1 ft = 0.30 m.

I use BTUs (British Thermal Units) to measure energy, but should you wish to enter the 21st century and use kilojoules (kJ) instead they are roughly equivalent: 1 BTU = 1.06 kJ.

Similarly, I use imperial R-values ($ft^2 \cdot °F \cdot hr/BTU$) and U-values ($BTU/ft^2 \cdot °F \cdot hr$) to measure insulation: $1\ ft^2 \cdot °F \cdot hr/BTU = 0.18\ m^2 \cdot °C/W$.

GOALS

As with any building project, you must determine your goals before any work begins. Setting your goals up front will help you determine your design requirements and how much your system will cost.

Fundamentally, the size, shape, and type of greenhouse you design will be determined by goals such as the type and number of plants you wish to grow, and the length of growing season you want to achieve. Let's look at some examples:

Example: greenhouse cannot freeze

Goals

- Mediterranean climate with perennial plants
- Year-round production of leafy greens
- Automated backup heating system

Design Implications

Although Mediterranean perennials can tolerate below-freezing temperatures, year-round production of leafy greens requires that your greenhouse never drop below freezing.

To achieve this goal you will need an auxiliary heating system, also a subterranean heating and cooling system—called a "climate battery" by early-adopter Jerome Osentowski— and sufficient thermal mass. (I describe these concepts later on.) The greenhouse also needs to keep in as much heat as possible, so it requires an insulated footing, extensive insulation in the walls, and perhaps even insulated blinds.

Example: greenhouse can freeze

Goals

- Three-season growing, primarily of annual plants
- A few perennial plants that grow only marginally outdoors, but would thrive in a greenhouse
- Early season seedling production for the outdoor garden

Design Implications

This greenhouse needs less insulation in the walls than in the first example, and may not need an insulated footing. A small rocket mass heater or wood stove can get you through the cold spells in the fall and spring. You may be able to get sufficient season extension just by adding thermal mass, but be sure the building is tightly sealed and well-ventilated.

You can go a step further with a subterranean heating and cooling system to moderate hot summer temperatures and to keep the greenhouse warmer in the spring and fall.

Minimum temperatures

One way to frame these goals—and a way that will make more sense later when we analyze heat loads—is the minimum temperature you will allow the greenhouse to reach.

USDA zones are used by gardeners to both describe the minimum temperature a geographic area experiences, and also to describe the minimum temperature a plant can tolerate.

Mediterranean perennials, for example, can grow in USDA zones 8 to 10. Zone 8 plants can tolerate winter cold down to -12°C, while zone 10 plants are only hardy to just below freezing.

Subtropical plants span USDA zones 10 to 13. Zone 13 plants can only tolerate temperatures down to 15°C. Clearly, a subtropical greenhouse will have to stay above freezing all year round, so will have a much higher heat requirement than a Mediterranean greenhouse that can drop below freezing for part of the year.

Growing lettuce all year round also requires the greenhouse to stay above freezing. If keeping your greenhouse frost-free is a priority, consider looking into subterranean heating and cooling systems that we describe in the "Heaters and Integrated Design" chapter.

RULES OF THUMB

- If you plan to grow in the winter, returns on production diminish rapidly as labour and other inputs increase dramatically.
- My goal to only extend the regular growing season saves time and energy by giving the greenhouse a winter's nap.

RESOURCES

Plants for a Future - 7000 Permaculture Plants: http://www.pfaf.org/user/default.aspx

Dynamic Accumulators: http://oregonbd.org/Class/accum.htm

Smith, Shane. *Greenhouse Gardener's Companion: Growing Food and Flowers in your Greenhouse or Sunspace*. Revised and expanded edition, Golden, CO, Fulcrum Publishing, 2000.

SITE SELECTION, ORIENTATION & ASPECT

Passive solar greenhouses depend on sufficient exposure to the sun, so choose a south-facing site with as few obstructions to the sun as possible. The greenhouse itself need not be oriented exactly to the south, however, as we discuss below.

SHADING AND SOLAR ACCESS

To establish the amount of solar energy a given site will potentially receive throughout the year—before considering reductions due to overcast or cloudy skies—the easiest way is to use a simple and cost-effective device that will last a lifetime: the Solar Pathfinder.

The Pathfinder is lightweight, optical (no electricity required), and simply sits on a small tripod. Regardless of the time of day or cloud cover, you can move it around and quickly assess multiple sites to measure the amount of direct sunlight a particular spot

Figure 1. The Solar Pathfinder is used to assess on site solar resources. www.solarpathfinder.com

receives at different times of the year. Use your measurements to choose the best site for your greenhouse, the one with the least shading from trees, buildings, and other obstructions.

The tool is very versatile and can be used to plan for passive solar buildings, photovoltaic electricity, and solar hot water. With add-on software you can produce professional reports very quickly.

Again, this tool does not account for the amount of solar radiation you will lose due to cloud cover in your area. For example, a greenhouse in cloudy Vancouver, BC, will get far less solar energy than a greenhouse with the same exposure in Calgary, Alberta. Later in the "Building Shape" chapter I discuss how glazing angle and other strategies can be tuned to cloud cover in your climate.

REAL PROPERTY REPORTS

A real property report is a great place to hand sketch the footprint of the greenhouse to see how it will integrate into the property. Take the sketch to your planning department to see if you are allowed to place your greenhouse where you want.

Orientation

Orientation is important, but don't fret if your site doesn't face perfectly south. Yes, the efficiency of the greenhouse decreases as the orientation of its long side deviates from facing south, but not by as much as you might expect.

If your greenhouse is 20° off of south, to either the east or west, it will receive a mere 4% less solar radiation than a greenhouse facing perfectly south. Going further, if your greenhouse is 45° off of south—southeast or southwest—that still only reduces the total solar energy collected by 18% relative to due-south.

Generally it is best to avoid western orientations—anything much past south-west—as the hot afternoon sun can make these greenhouses very tough to cool. Preferably, your greenhouse will face south to south-east.

Slope

Both flat and sloped sites have advantages for passive greenhouses. Flat sites make site prep and construction much easier, but sloped sites allow you to build the greenhouse into the side of the slope, a considerable advantage for winter heating.

Aspect ratio and height

The ratio of the greenhouse's length to its width is called the "aspect ratio." My greenhouse in Calgary is 20 feet long and 10 feet wide, so has an aspect ratio of 2:1.

Whether it's a small or large greenhouse, the best aspect ratio for passive solar is in the range of 2:1 to 3:1. This shape optimizes solar gain, minimizing energy needs for heating and lighting.

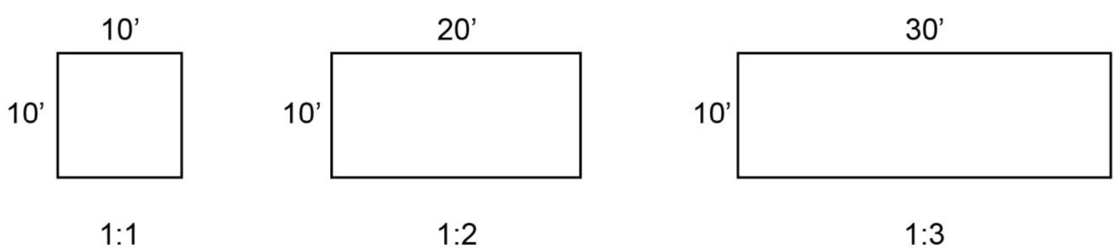

Figure 2. Aspect ratios

The height is determined by a number of factors: 1) the height of the knee wall, 2) the height of the southern ventilation pane, and 3) the slope of the roof that you choose.

To create good cross-flow ventilation, the highest point—and vents—should be on the north wall, inducing a draft from the low vents on the south wall.

RULES OF THUMB

- The long side should face within 20 degrees of true south, either east or west.
- The length should be two or three times the width.

RESOURCES

- Solar Pathfinders can be purchased here: http://www.solarpathfinder.com/

BUILDING SHAPE

The profile of the greenhouse from south to north consists of a vertical knee wall and ventilation louvres, angled glazing (transparent material), a north-sloping roof and, sometimes, a vertical back wall. The shape also depends on whether you are building a greenhouse with a large or small footprint.

Angled glazing

The angle or slope of the glazing—be it glass, polycarbonate, or some other material—is an important design decision. For more on materials, see the chapter on "Glazing & Light".

The best angle for your design, however, may have more to do with shedding snow loads or matching the dimensions of available materials than it does optimizing the angle for heat and light.

In areas with snow loads, it's important to make the angle steep enough to reliably shed the snow. If a roof must support a snow load, the additional strength required rises construction costs dramatically.

The optimal angle to maximize heat and light in the greenhouse depends on the time of year you plan to do most of your growing, and also whether your winters are cloudy or clear. The more glazing faces directly at the sun's rays—that is, the more perpendicular the glazing is to the sun—the better the solar gain.

Glazing angles are measured from horizontal—i.e. 90° means vertical. The optimal glazing angle for clear winter days is found by this rule of thumb: Add 15° to your latitude. In Calgary, for example, the latitude is 51° and we have lots of clear winter days, so the optimal angle is 66°.

The exact angle is not critical, however. In fact, as long as the glazing angle is between 45° and 70°, your solar heat gain will be within 5% of what it would be at the optimal angle. This is partly because high-tech materials such as polycarbonate, reflect less and diffuse more light than glass. The net result is that glazing angle is less important with polycarbonates than it used to be for glass-houses.

The sun is higher in the sky in summer, and lower in the sky in winter, so steeper glazing angles increase the solar heat gain on clear days in winter, and decrease it in summer—a good thing to reduce overheating.

When it's overcast, however, light is scattered or "diffused" by clouds, so the benefits of steep glazing are significantly reduced. In places with lots of overcast days, like Vancouver, you will want to use a much shallower glazing angle to allow more of the diffuse light in.

You will also want to use shallower glazing angles if you plan to do most of your growing in the spring and fall when the sun is higher than it is in winter.

Shallow roofs require a taller knee wall and back wall, as well as a strong truss system to hold the glazing up in areas with large snow loads. As I noted earlier, this increases building costs.

Recall that roof slope is one of three factors that affect the height of the greenhouse, so it often makes more sense to consider height restrictions and material constraints first, before designing to the optimal glazing angle. In a city, for example, your greenhouse may have to conform to bylaws that will determine how steep or shallow the angle can be.

Knee wall and ventilation louvres

The knee wall is the south vertical wall, usually about the height of a knee, that rises to meet the ventilation louvres below the glazing. The knee wall is usually simple, with little to no glazing, operable doors, or windows.

Because snow accumulates against the knee wall, it has to be strong enough to take the one-sided load. The wall must also have the correct surface treatment to withstand moisture.

Most importantly, the knee wall needs to be tall enough for snow to accumulate in front of it without blocking the ventilation louvres or the glazing. To deal with all the snow that slides off the glazing as well, the required height for the knee wall is considerably more than just the average annual snowfall.

MISTAKES I MADE—KNEE WALL

My raised beds block the vents at the front of the greenhouse. A knee wall would have solved this problem, so we plan to turn the vent wall into a knee wall and move the vents up into the glazing surface.

In extreme climates you may need to clear snow from the area below the glazing to prevent damming, so make sure you have winter access to the south side.

A tall knee wall is less important for a small footprint greenhouse as the glazing is typically much steeper and so will accumulate less snow. In my climate, a three-foot knee wall for a small greenhouse should be sufficient. For a large greenhouse, four feet is considered the minimum knee wall height.

There is plenty of leeway in the choice of knee wall height which gives us flexibility as we manipulate the shape of the rest of the greenhouse.

Small greenhouse

Small greenhouses may have to consider steeper angles than are optimal to keep the overall dimensions reasonable. Again, keeping the angle between 45 and 70° will optimize solar gain in the winter months and still keep the footprint small.

Below I've adapted James McCullagh's steps to designing the profile of a small footprint greenhouse from *The Solar Greenhouse Book* published by Rodale Press—see Figure 3 and Figure 4.

Steps to design a small greenhouse

1. Determine your main limiting factor—length or width—and then choose an aspect ratio between 2:1 and 3:1 to make the best use of the space. For example, if your site is only 10 feet wide but 30 feet long, you could build a 10 foot wide greenhouse with either a 2:1 or 3:1 aspect ratio to fill the available space.

2. Determine the angle of the glazed south face of the greenhouse and draw a line with this angle on graph paper to start your profile design. Don't worry about knee walls yet.

3. Decide how high the top of your greenhouse should be. Again, ask your planning department if bylaws might limit your design. Nine to twelve feet is a good height for a family-sized greenhouse. Draw a vertical line to intersect with the south slope and mark the peak of the greenhouse.

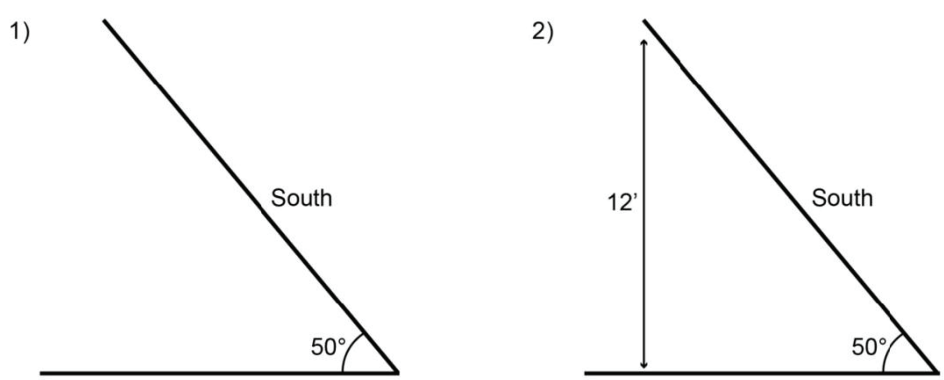

Figure 3. Determine glazing angle and peak height. Illustration from The Solar Greenhouse Book, *Rodale Press.*

4. For most of North America, a rear slope of 65° to 75° is acceptable to shed snow. Any steeper and you'd lose a lot of headroom, depending on the glazing angle you choose. From the peak, draw this line down to the ground level on your graph paper.

5. Measure the width of the greenhouse based on the slopes and height chosen in steps 2 to 4. You may want to experiment and go through several iterations of these steps until you are satisfied with the angles, height, width, and growing area.

6. You can use knee walls to compromise between your "ideal" angles and practical considerations such as material lengths, width, and headroom. The height of the knee wall affects solar efficiency, ease of building, maintenance, and how you are able to use the space.

7. To get the floor area you need, consider making your greenhouse longer rather than changing the angles that you determined to maximize the most solar energy getting into your greenhouse.

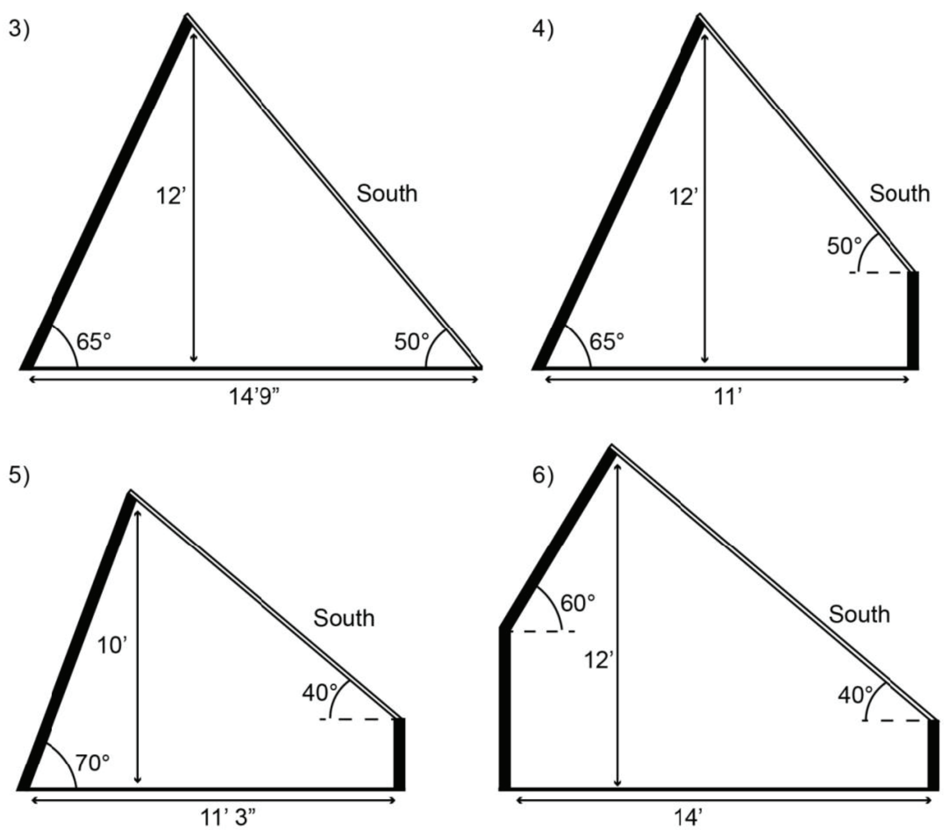

Figure 4. Determine roof slope, width, and wall heights. Illustration from The Solar Greenhouse Book, *Rodale Press.*

To see how we applied these steps in the design of our solar greenhouse, see our blog: [How we Designed our Solar Greenhouse.]

Large greenhouse

If you are building a large greenhouse like the ones Jerome Osentowski builds at the Central Rocky Mountain Permaculture Institute, your glazing angle will be determined by snow load and the overall width of the greenhouse rather than optimal solar gain.

Consequently, the cross-sectional shape for the larger-style solar greenhouse is slightly different than the smaller, solar-optimized greenhouse design, as you can see in Figure 5 below.

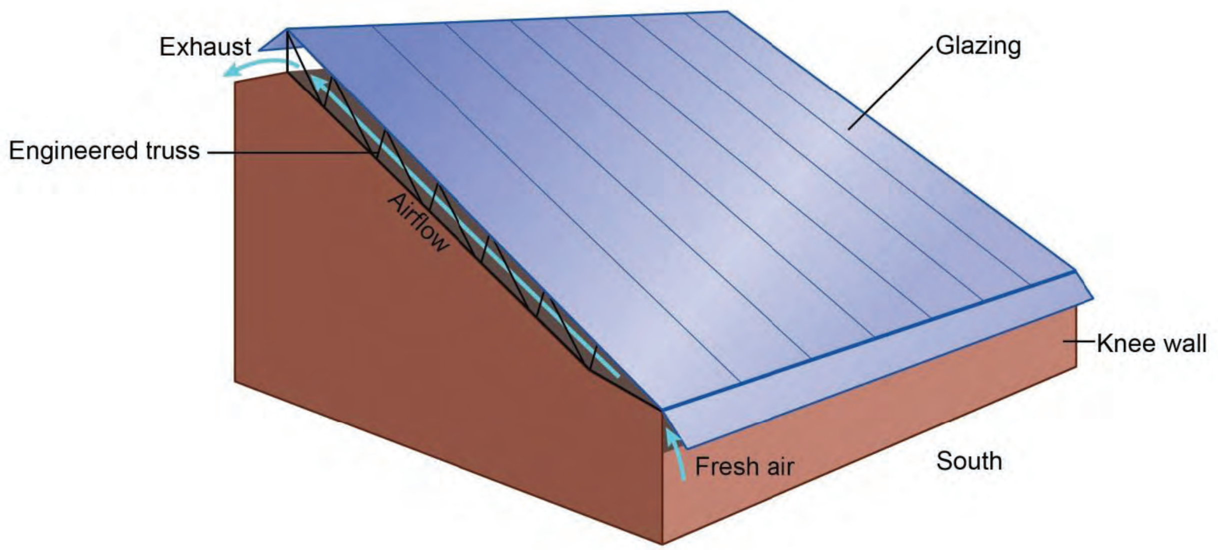

Figure 5. Typical large greenhouse shape and components

As the greenhouse gets larger, the height required for steep angles becomes impractical, so the design is constrained to shallower angles. The final decision is usually based on the price of steel and how much snow you need to shed, with typical roof pitches for larger greenhouses ranging from 6:12 (26.5°) to 8:12 (33°).

See Table 1 for information on common roof pitches and their angle from horizontal.

It's important to design the glazing trusses to support the snow load for your area. We highly recommend consulting a civil engineer to ensure that the structural components of your greenhouse are designed appropriately.

Steps to design a large greenhouse

1. As for a small greenhouse, determine your main limiting factor—length or width—and then choose an aspect ratio between 2:1 and 3:1 to make best use of the space.

2. Determine how high your knee wall will have to be to manage the snow sliding from the roof. If a short knee wall is desired, ensure that there is a snow removal plan.

3. Engage a civil engineer to determine how steep your southern glazing surface should be to manage the load. Note that your choice of glazing—see the "Glazing & Light" chapter—will affect this decision. For cold climates do not choose anything less than 16 mm.

4. Once you've chosen the knee wall height and the pitch of the glazing surface, the size of the sidewalls and the rear wall will become evident.

Pitch	Angle
4:12	18.4°
6:12	26.5°
8:12	33.7°
10:12	39.8°
12:12	45.0°

Table 1. Common roof pitches and their associated angle.

RULES OF THUMB

- To optimize the glazing angle for winter growing with clear days in small greenhouses, add 15° to your latitude.
- Shallower roofs give more solar heat gain in overcast climates and in spring and fall.
- Glazing between 45° and 70° will gain within 5% of the solar heat that would be gained at the optimal angle.
- Typical roof pitches for large greenhouses range from 26.5° to 33°.
- A knee wall needs to be tall enough that the ventilation louvres above it aren't blocked by snow that accumulates, both as direct snowfall and snow that slides off the glazing.
- Give yourself access to the south side if you think you may have to dig it out occasionally.

RESOURCES

- McCullagh, James C.. *The Solar Greenhouse Book*, Emmaus, PA, Rodale Press, 1978
- *How We Designed Our Solar Greenhouse:* http://vergepermaculture.ca/blog/2011/01/09/how-we-designed-our-solar-greenhouse/

FOUNDATIONS AND SOIL

Ideally you want to have piers, screw piles, insulated concrete forms (ICF), or an insulated concrete wall to support your greenhouse.

All of these types of foundation give your plants access to the subsoil and the enormous amount of micro-nutrients which the soil food web mines for plants. The subsoil offers a real advantage for larger plants and can also avoid drainage issues.

By the same token, avoid using a concrete slab if it's at all possible. Slabs force you to grow in raised beds—see Figure 6—which are hard to keep nutrient dense.

MISTAKES I MADE—CONCRETE PAD

We can't grow in the ground because of the concrete pad under my greenhouse, so we have to grow in containers.

The subsoil is one of the most nutrient dense materials that exists, so when you disconnect your plants from it, you end up having to add nutrients constantly to make up for deficiencies.

Most plant diseases can be avoided with proper nutrition, and the converse is also true.

Whatever foundation you choose, it's critical to insulate it to the frost line to keep frost out of the growing beds. Check with your local building authorities to determine the frost line's depth in your region. In most of Alberta, for example, it is between 4 to 6 feet below the surface.

You may not need a full frost wall if you plan to let the greenhouse freeze through the winter, for example if you intend to grow subtropical plants or delicate greens.

This approach can provide considerable cost savings: you may be able to avoid a continuous foundation entirely and use inexpensive piers (also known as sono tubes) instead.

MISTAKES I CORRECTED—RAISED BEDS

Necessity is the mother of invention, and I solved the problem of building on a concrete pad with special raised beds. My blog has much more information on how I designed these wicking beds.

Figure 6. Raised "wicking" beds in the greenhouse

ALTERNATIVE FOUNDATIONS

If a full depth frost wall using concrete or ICF bricks is not in the budget, there are alternative foundations you can research, such as these:

- Shallow insulated foundation
- Insulated rubble trench

Shallow insulated foundation

Shallow insulated foundations use foam insulation that projects out from the edge of the building horizontally instead of being buried vertically. This saves you having to dig to frost line—6 feet deep where I live—to achieve the same frost protection. Unfortunately, the horizontal foam also creates a "dead zone" above the insulation where moisture can not travel up or down.

Rubble trench foundation

The rubble trench is one of the longest lasting and— if you are doing it yourself—one of the least expensive foundations, but ironically it does not get used all that often. Here is a great online resource to build rubble trench foundations, but there's no need to use a concrete slab like they did.

Regardless of which style of foundation you choose, it is best to have a civil engineer or architect design the building foundation for you.

THE IMPORTANCE OF SOIL

The operation of a successful growing space depends fundamentally on the soil in your greenhouse. If you are getting diseased plants, low yields, or bug infestations, look into your soil health and consider regular additions of mulch, worm castings, compost and compost tea.

RULES OF THUMB

- To grow all year, you will need to install frost walls around the base of the greenhouse to keep frost out of the building.
- To simply extend the regular growing season—or for hardier plants—an insulated footing may not be as important.

RESOURCES

- Rubble trench foundations: http://www.buildnaturally.com/EDucate/Articles/RubbleTrench.htm
- *Teaming with Microbes: The Organic Gardener's Guide to the Soil Food Web*, by Jeff Lowenfelds and Wayne Lewis. (My favourite soil book, and the one I recommend everyone read!)
- Soil: http://vergepermaculture.ca/blog/2010/06/02/story-soil/
- Soil health: http://vergepermaculture.ca/blog/2012/05/08/soil-results-are-in/
- Worm castings: http://vergepermaculture.ca/blog/2011/03/01/everything-you-need-know-about-composting-worms-2/
- Compost teas and extracts: http://vergepermaculture.ca/blog/2012/06/14/compost-brews/
- Wicking beds: http://vergepermaculture.ca/blog/2011/05/30/guide-to-wicking-beds/

VENTILATION

Greenhouses require lots of ventilation, ideally enough to keep the indoor temperatures below 29°C. Any hotter and heat stress can stunt or damage the plants, increase the risk of diseases such as powdery mildew, and reduce the ability of plants to flower and set fruit.

At the other end of the spectrum, minimum temperatures clearly depend on what you plan to grow, but ideally they don't dip below 10°C or 15°C. Colder than that and photosynthesis stops or slows down significantly.

Finally, keep in mind that CO_2 is essential for efficient photosynthesis. If you regularly add mulch to the soil, the constant decomposition will release ample CO_2 into the greenhouse.

Moving air

Air movement in the greenhouse is critical. If you get the ventilation right you can usually avoid using fans.

Start your ventilation design with two-foot high louvres—operational ventilation panels—along the entire length of the knee wall. These south-side fresh air intakes sit immediately below the glazing.

These "low vents" bring in fresh air that warms and rises in the greenhouse. To exhaust the hot air, design in louvres at the very peak of the greenhouse. The total area of these "high vents" is ideally 15% more than the low vents to account for the expansion of air as it heats up.

The goal is to establish a natural cross flow through the greenhouse without fans. Having low and high vents is an effective way to get this kind of cross flow by encouraging a natural thermosyphon.

Looking at the details of this thermosyphon cross flow, as in Figure 7, cool air enters above the knee wall flows up along the glazing—heating up as it goes—and exits at the peak. Because both low and high vents run the full length of the greenhouse, the ventilation flows across the entire glazed surface.

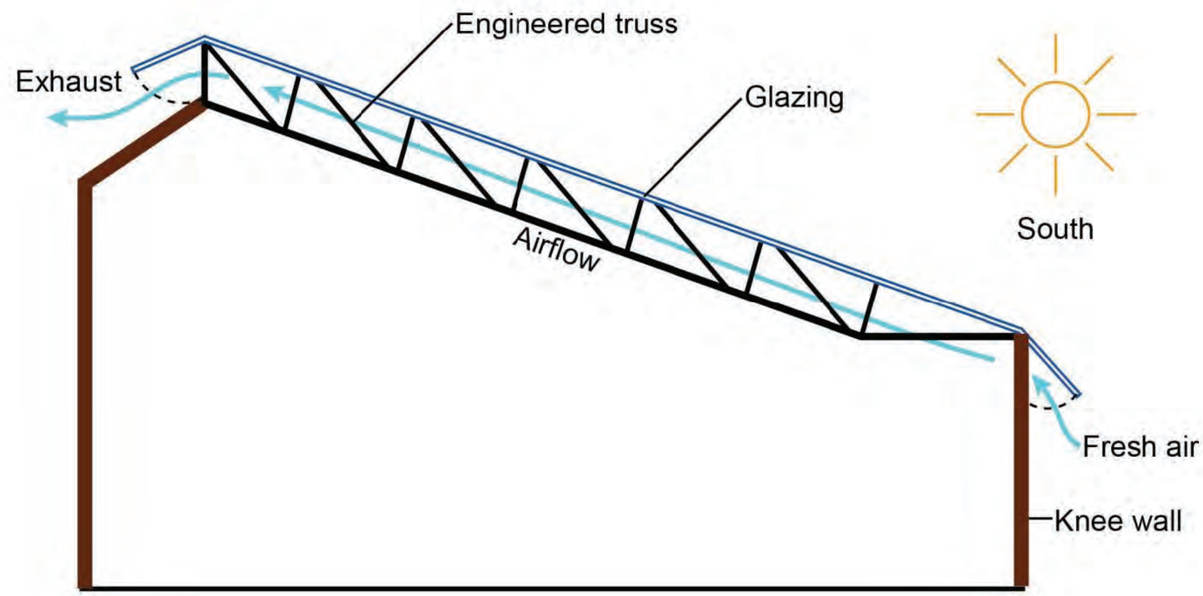

Figure 7. Ventilation louvre locations at the Central Rocky Mountain Permaculture Institute.

Adjusting temperatures

The amount the ventilation panels are open can be adjusted to moderate the temperature inside, but don't close them down completely unless the temperature outside drops below freezing.

Vents can be automated with "solar motive cylinders" that use gas or wax in a cylinder that expands when it's hot, opening the vent, and contracts when it's cold to close the vent.

For example, all the ventilation louvres at the Central Rocky Mountain Permaculture Institute (Figure 7) can be opened with either motorized or solar motive cylinders.

Despite your best ventilation efforts, it may still get too hot in the summer. If so, you may need to install a shade cloth under the south eave to reduce the heating load.

When winter looms at the end of the year, make sure you weather-strip all vents and doors, and caulk all cracks. This is very important! Even a small draft can work against you in a big way, especially if you have lots of thermal mass, as we'll discuss later.

MISTAKES I MADE—VENTILATION

My biggest mistake of all was not putting enough ventilation up on the rear wall or roof. There wasn't enough airflow and the greenhouse would overheat, stressing the plants and causing diseases like powdery mildew and blossom end rot.

Fans have solved the problem for the moment, but as soon as we install additional ventilation up top, the fans will rarely be needed.

Figure 8. Fans can compensate for inadequate ventilation

Vestibules and breakout doors

Besides access and a view, doors and windows on the east and west ends of the greenhouse also play an important role in ventilation, allowing natural cross-drafts to increase air movement. Two other features can make the ends even more functional: vestibules and breakout doors.

Breakout Door

I am very happy with the breakout door in my greenhouse, and I think every greenhouse should have these to allow for future design changes. The 4-foot by 5-foot door is easily removed with screws and is large enough to allow me to move big tanks and other big materials in and out of the space without being limited by a small door.

Better yet in the middle of summer, I can open it right up to increase drafts in the space, keeping the building much cooler on really hot days.

Figure 9. The outline of the breakout door is visible below the chimney.

Vestibule

On the other side of the year, vestibules can be a real boon. A vestibule is a small, enclosed entrance room that prevents a blast of cold air from rushing in and freezing your plants when you enter the greenhouse. The colder the air is outside, the faster the warm

Figure 10. Plastic strips hung in doorways help to reduce heat exchange.

air will escape and cold air will enter. Without the two-door system of a vestibule, this cold air can be a real shock to the greenhouse.

If you don't have room for a vestibule you can use transparent plastic strips in the entrance (Figure 10). These are typically used in cold storage facilities to stop cold air mingling with warm air.

Condensation

Condensation can deteriorate materials very quickly if there is no way for the water to shed from the surface. Tilt surfaces to allow condensation to run off by gravity. Consider tilting or bevelling structural areas that are normally flat, such as window sills, to avoid rot.

If you plan to have any hard floors—concrete, flag stone, pavers, etc.—make sure you design them on a slight slope towards a floor drain so water doesn't pool.

Attaching a greenhouse to existing structures

Condensation and humidity problems are the bane of attached greenhouses, so generally I do not recommend this approach unless you are an expert in building science or are advised by someone who is.

Greenhouses are humid, and with the wrong materials or design that moisture can work its way into your external walls and cause black mould, for which repairs are expensive and sometimes impossible.

The temptation to attach the greenhouse to another building, however, is strong: it promises to lower building costs by sharing the existing north wall, the two buildings can share heat, and it often puts the greenhouse closer to the kitchen.

You can successfully attach a greenhouses to buildings made from concrete, sealed cinder block, and structurally insulated panels (SIPs) that are either waterproof or vapour proof. Steel, aluminum, and Styrofoam SIPs are acceptable, but SIPs made from oriented strand board are not appropriate.

Make sure the total venting area of an attached greenhouse—high and low vents—equal about 25% to 30% of the total area of glazing. The door can be added to the total venting area if you are able (or willing) to open and close it every day as needed.

RULES OF THUMB

- The ideal temperature range for greenhouse operation is 10°C to 29°C for most plants.
- High vents should have 15% more total area than the low vents.
- For attached greenhouses, total venting area should equal 25% to 30% of the total area of glazing.
- Vent area needs can be significantly reduced with an exhaust fan.
- Use doors and windows on the east and west ends for cross-drafts.

GLAZING & LIGHT

Glazing—usually sheets of glass or plastic—allows the sun's light and heat to enter. But this strength by day is its weakness at night when it loses large amounts of heat, far more than is lost through the insulated walls and roof.

Light is important, and a lack of it can seriously limit greenhouse plants, especially in the winter months. Brightness is determined not only by the glazing's transmissivity, but also by the reflectivity of the walls inside the greenhouse.

Transmissivity

A glazing's transmissivity is the amount of light it lets through, where its thermal resistance is its ability to insulate and keep heat in. As you increase the thickness of the glazing, you increase the thermal resistance, but you simultaneously reduce the transmissivity.

If transmissivity is too low, your plants can suffer light deprivation, so your glazing should have a minimum transmissivity of 70%. This sets an upper limit to how insulative the glazing can be.

MISTAKES I MADE—SUNLIGHT DEFICIENCY

I built an overhang on the greenhouse to be a drip edge and also to prevent mid-summer overheating. Unfortunately the overhang also reduces the amount of sunlight that reaches the back of the greenhouse.

I still think the overhang is a good idea, so in a future retrofit I am going to install a series of operable skylights.

Polycarbonate

I recommend either five or three cell polycarbonate material. Five cell (25 mm) is much better than three cell (16 mm), which we suggest is the minimum thickness. Table 2 gives an idea of the typical properties of some brands of polycarbonate glazing.

Polycarbonate is not only hail resistant, but has the ability to diffuse, or break up the light spectrum. Diffused light increases plant photosynthesis. In fact, plants grow better under glazing that is not crystal clear. Diffused light is also distributed more evenly to plants in shadier areas than it would be if the glazing were clear.

To keep the transmissivity high, dirty glazing needs to be cleaned and polycarbonate that yellows needs to be replaced.

Product	Manufacturer	Thickness (mm)	R value	U value	Transmissivity
Triple Wall	Co-Ex Corp	10	2.1	0.47	75%
Triple Wall	Co Ex Corp	16	2.6	0.38	72%
Multiwall Polycarbonate	AC Plastics	10	2.1	0.48	75%
Multiwall Polycarbonate	AC Plastics	16	3.0	0.34	62%
Triple Clear	Poly Gal	10	3.0	0.33	79%
Thermogal	Poly Gal	25	3.2	0.31	79%

Table 2. Typical polycarbonate glazing materials and their thickness, R value, and transmissivity.

Light

Light needs vary depending on the species, spacing, and density of leaves. For example, some sub-tropical and Mediterranean plants have adapted to grow in the lower light conditions under a forested canopy. Others go dormant during the cold months and so do not require light through the dark months.

Symptoms of low-light conditions

- Spindly, slender growth
- Slow growth
- Plants bend drastically towards the light
- Yellowing lower leaves—this is also a symptom of nitrogen deficiency

On a good sunny day around noon, vegetables typically need between 700 to 1,000 foot-candles—a foot-candle is one lumen per square foot.

You may have to purchase a light meter to determine this. They are generally fairly cheap and you should be able to get a decent meter for about $30 to $100—check the internet and your local hydroponic supply store. Alternatively, if you have a smart phone, you can download a light meter app.

Reflective walls

To increase the available light, you need to increase the reflectivity of the walls. This is most easily achieved by painting the interior surfaces white, including the walls, ceilings, floors and even the sides of raised beds.

Use a high-quality gloss or semi-gloss "snow" white, mildew-resistant paint such as those recommended for bathrooms.

To store heat for the winter months, however, you also need to absorb heat with elements such as cob structures, rock walls, and water barrels—I describe this in more detail in the "Thermal Mass" chapter.

Painting these elements dark colors encourages heat absorption. In the summer when you want to reduce heat absorption to keep it cooler, you may want to cover these elements up with white sheets, or encourage perennial plants to grow over them.

RESOURCES—GLAZING MANUFACTURERS

- CoEx Corp: http://www.co-excorp.com
- AC Plastics: http://www.acplasticsinc.com/
- Poly Gal: http://www.polygal-northamerica.com/
- Acrylco Manufacturing (Calgary Distributor of Glazing Materials): http://www.acrylco.com/

RULES OF THUMB

- Use at least triple wall, 16 mm polycarbonate for glazing.
- Five layer, 25 mm polycarbonate glazing is much better.
- Keep your glazing clean and replace it when it yellows.
- Aim for about 1000 foot-candles of light on a good sunny day at noon.
- Use a high quality, gloss or semi-gloss, white, mildew-resistant "bathroom" paint on all surfaces.
- The sun-absorbing side of thermal masses should be dark.

THERMAL MASS

Dense materials like water and rock hold their temperature better than air, providing "inertia" against wide temperature fluctuations in the greenhouse. Like a rechargeable battery for temperature, thermal masses absorb heat when the surroundings are hotter—cooling the area—and release heat when the surroundings are cooler, heating the area.

Like the name suggests, the effectiveness of a thermal mass depends on its mass, as well as properties specific to each material that determine its "heat capacity," the amount of thermal energy (measured in kilojoules, kJ) a unit mass (kg) will store per unit temperature (°C).

Material	Heat Capacity (kJ/kg/°C)
Water	4.18
Wax	2.9 to 3.4
Wood	2.0 to 2.9
Plastic (foam to solid)	1.3 to 1.7
Soil (dry to wet)	0.8 to 1.5
Rock, concrete, cob	0.7 to 1.0
Steel	0.49

Table 3. Common materials used as thermal masses in greenhouses, and their associated heat capacities The larger the number, the more thermal energy a given mass can store.

Common thermal mass materials include water, rock, cob, concrete, brick, soil, and wood. See Table 3 for approximate heat capacities.

Thermal mass is usually located along the north wall. Wide greenhouses may also place some thermal storage on the south wall or in the middle of the greenhouse, but try to avoid shading plants.

Storing heat with water

Water has the highest heat capacity, holding five times more thermal energy per kilogram than granite. Better yet, as temperatures drop to zero, ice crystals form in the water giving off a "latent" heat that helps warm the greenhouse.

The most common type of thermal mass in greenhouses is water stored in containers such as 50-gallon barrels or rain tanks. Clearly, water storages are also useful to collect rainwater and irrigate with warm water, but note that as your reservoirs are drained to irrigate, you also lose the thermal mass.

Containers can be inexpensive if you find them used, and they can be painted black to increase heat absorption in the winter. In summer, hang a white curtain in front of them to increase light availability.

That said, barrels take up a lot of valuable floor space and don't fill a square space efficiently. And in cold climates I prefer rock and cob-based systems because problems can be caused by freeze-thaw expansion and contraction of water. If you do use water for thermal mass in cold climates, avoid cracking your tanks by leaving them open or less than full.

Figure 11. Slim line rain tanks use space efficiently to hold rain water for irrigation and thermal mass, but be cautious about freeze-thaw problems.

Storing heat with cob and rock

Retaining walls, boulders, gabion walls—steel cages filled with rock, see Figure 12— and cob benches are just some of the elements a greenhouse design can use to increase thermal mass.

Cob is made as a wet mixture of clay and sand to which fibres like straw are added. The mixture can be formed into features like benches that dry hard and strong. Cob benches are often paired with "rocket mass heaters." (See the "Heaters and Integrated Design" chapter.)

Figure 12. This gabion rock wall would be a great back wall: It uses vertical space, inexpensive rock, and it looks beautiful.

As I mentioned earlier in the "Light" chapter, paint thermal masses black on their south side to absorb solar energy, but paint them a white on the north side to increase available light.

WAX ON, WAX OFF

Not only does solid wax have a heat capacity almost as high as water, (see Table 3) but it stores much more heat again when it melts.

During the "phase change" transition from solid to liquid, wax stores lots of energy and fiercely resists temperature changes in the space around it. Lots of thermal mass research is now focused on materials that change phase at greenhouse temperatures.

Storing heat with soil and plants

Soil and wood are also good thermal masses, and one of the many benefits of having perennial plants and trees in a greenhouse is their high heat capacity.

I could not find a measurement for the heat capacity of a living tree, but a living tree's mass is between one-quarter and three-quarters water—depending on the species and other factors—so a tree's heat capacity will be between wood and water (Table 3). This is one reason why greenhouses growing perennials have more stable climates than those growing annuals.

RULES OF THUMB

- The amount of thermal mass required depends on many variables, but in general use more for poorly sealed greenhouses, or for greenhouses in cold, cloudy climates.
- For water as thermal mass, provide at least 2 to 3 gallons of water for each square foot of glazing.
- For cob, concrete, or rock you will need five times as much mass as you would if you were using water, so approximately 40 to 60 kg per square foot of glazing.

RESOURCES

- Heat capacities: http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
- The Center for Rain Water Harvesting: http://www.thecenterforrainwaterharvesting.org/
- Brad Lancaster's website: http://www.harvestingrainwater.com/
- American Rainwater Catchment Systems Association: www.arcsa.org/

INSULATION

Some insulation is necessary, but heat loss through the glazing will far exceed any heat loss through the walls. Consequently, adding more insulation to the walls will, at a certain point, do very little to reduce heat loss.

So, before you go overboard with insulation in the walls and roof, make sure you do a heat load analysis—see the"Heat Load Analysis" chapter—to identify your biggest heat losses.

Insulation is measured by R-values, the thermal resistance, or U-values, the thermal conductivity. U-values and R-values are the inverse of each other: U = 1/R and R = 1/U. Where a higher R-value indicates a material resists the movement of heat, a higher U-value indicates a material more efficiently transfers heat.

R-values—$ft^2 \cdot °F \cdot hr/BTU$—are more commonly used and are perhaps easier to understand, but U-values—BTU/(h °F ft2)—are used in calculations like heat load analysis.

UNITS

I use imperial units for insulation and heaters because that is the standard for the North American construction industry.

$$1\ m^2 \cdot °C/W = 5.68\ ft^2 \cdot °F \cdot hr/BTU$$

Typically you'll want values around R12 or greater for your frost wall, R20 to R36 in all the walls, and R30 to R40 in the roof. These numbers are a rough guide and what's best for you will depend on the severity of your climate and your goals. Generally, insulating beyond R50 will not bring additional benefits.

Table 4 lists some typical materials used for insulation and their R-value per inch. For example, two inches of extruded polystyrene, R5 per inch, has a total value of R10.

Material	R-value per inch
Phenolic Foam	8.3
Sprayed Polyurethane Foam	6.9
Extruded Polystyrene	5.0
Rock Wool	4.3
Pink Fiberglass Insulation	3.9
Expanded Polystyrene	3.8
Perlite	2.8

Table 4. Typical insulation materials and their R-value per inch.

The U-values and R-values of some commonly constructed walls are given inTable 5. If your building product is not listed here, ask the manufacturer.

Note that SIPs (Structurally Insulated Panels) come in many different styles. They are high or low density foam sandwiched between two layers of oriented strand board (a wood product), steel, aluminum or magnesium oxide. Greenhouses are typically very humid, so choose a SIP made from materials that can handle damp conditions.

Insulated Blinds

Even high performance glazing is typically in the range of R2 to R3. For this reason, insulated blinds can make a huge difference in the performance of the building.

Insulated blinds reduce the energy lost through glazing on cold nights, and can have a huge impact on the warmth of your structure. There are many options, but blinds will usually improve the R-value of the glazed surface from R2 to R4.

This may still seem low, but doubling the R-value of this "weakest link" does have a dramatic impact on heat loss. When you do your heat loss analysis, below, try it both with and without insulated blinds to see the difference.

Some blinds are installed inside the greenhouse, and others drape over the glazing on the outside. If you get freezing rain, I highly recommend that you do not use external blinds as they can stick to the greenhouse.

You can purchase custom blinds from a number of specialized blind manufacturers or you can go to a local awning and tent manufacturer and have them build you an insulated curtain. They may also be able to help with automation—our local manufacturer does custom work and I have found them to be extremely ingenious in managing materials.

Building Element	U-value	R-value
2X4 wood framed wall with fiberglass insulation	0.061	16.5
2X6 wood framed wall with fiberglass insulation	0.050	20.0
2X4 wood frame with polyurethane insulation	0.040	25.0
2X6 wood frame with polyurethane insulation	0.030	33.0
2x4 SIP with EPS insulation	0.080	12.5
2X6 SIP with EPS insulation	0.054	18.5
2X8 SIP with EPS insulation	0.041	24.5

Table 5. Typical building components and their associated U and R values.

Automation can save a lot of labour. Otherwise you have to go out every morning and every night to open and close the blinds.

You can also build yourself blinds using insulated construction tarps and manage them manually. Suspend them by their metal eyelets on high tensile airplane wire fixed to the sides of the greenhouse, parallel to the glazing. With a spreader bar and pulley, you can pull the curtain up and let it down very easily.

Low Cost Insulation Material

Our world is full of trash that can be reused with a little innovation, keeping costs low and material out of our landfills.

Colleagues of mine in British Columbia have come up with a unique way to build and insulate their foundations, footings, and even walls with the foam seedling trays (EPS trays)used by the forestry industry and typically landfilled after just one to three uses. Figure 13 and Figure 14 show how they build with these blocks.

Please note that these systems are not engineered, so use them at your own risk.

Figure 13. Tree Seedling trays being strapped together with pallet straps, and then assembled into an insulated footing for a yurt.

Figure 14. Seedling trays adapted to be ICF (Insulated Concrete Form) bricks, and then filled with concrete.

RULES OF THUMB

- R12 or greater for your frost wall.
- R20 to R36 in all the walls—north back wall, east and west side walls, and south knee wall.
- R30 to R40 in the roof.
- Don't bother insulating beyond R50.
- Use insulated blinds to double the R-value of glazing, typically from R2 to R4.

RESOURCES

- Blind manufacturer: http://www.aprgreenhouses.com/index.php/en/thermal-and-shade-screens

HEAT LOAD ANALYSIS

Heat load analysis is a way to determine how much supplemental heat you'll need to keep your greenhouse at the desired temperature throughout your climate's cold season. I'll do a simple analysis here so you can do one for your own greenhouse.

In short, we calculate heat loss for the worst-case scenario and use that number to select a heating device to match worst-case losses.

Heat loss

The least expensive way to heat buildings is to minimize heat loss. If you've got a building that loses a lot of heat and also has a lot of thermal mass, heaters are even less effective as they fight against the cold mass.

The biggest heat losses are typically due to infiltration—drafts through unsealed joints—and through the glazing. I show below how insulated blinds can dramatically improve glazing losses, and infiltration losses can usually be prevented with caulking and weatherstripping.

Calculations

First we estimate heat loss for a worst-case scenario of no sun and the coldest outdoor temperature. The amount of heat lost depends on the temperature inside the greenhouse, so we choose—based on our growing goals—the minimum temperature we will allow the greenhouse to reach.

HEAT LOSS EQUATION

$$H = U \cdot A \cdot (t_{in} - t_{out})$$

Heat loss through materials can be estimated with a simple equation—above—where **H**, heat loss per hour (BTU/hr), is the product of:

- **U**, the thermal efficiency of the material (BTU/hr °F ft^2), as described in the "Insulation" chapter,
- **A**, the area of the material (ft^2), for example $32ft^2$ for a 4-foot by 8-foot sheet,
- and **(t_{in} - t_{out})**, the difference between t_{in}, the indoor temperature, and t_{out}, the outside temperature (°F).

For t_{in} use the minimum allowable indoor temperature based on your goals, be they Mediterranean, subtropical, or otherwise. The minimum is typically dictated by the most sensitive plant in the greenhouse.

For t_{out} use the extreme minimum annual outdoor temperature—recall that we're after a "worst-case" estimate.

We'll use this equation several times in an example below to measure the heat loss through all the major components in my greenhouse. You'll be able to use the same approach to estimate heat loss in your own design.

Extreme temperatures and heating degree days

To get a heat loss estimate, first you need to know your climate's extreme minimum temperature in °F. Table 6 has data for a few Canadian cities.

I've also included data for "heating degree days" (HDD), a measurement that reflects the energy needed to heat a building. You don't have to know the HDD in your climate, but you may find it useful to compare the heating demand on your greenhouse relative to other regions.

A higher HDD means more heat is required to keep a building warm. More specifically, heating requirements for a given structure are directly proportional to the location's HDD, which is derived from measurements of outside air temperature throughout the year and compared to a base indoor temperature, usually 16°C or 18°C.

City	Extreme Low (°C)	Extreme Low (°F)	Avg. Temp. January (°C)	HDD (°C)
Saskatoon	-50	-58	-17	5852
Quebec	-36	-33	-13	5201
Fredericton	-37	-35	-10	4750
Calgary	-40	-40	-9	4129
Toronto	-33	-27	-4	3569
Vancouver	-18	0	3.3	2782

Table 6. Representative Canadian cities and their extreme minimum temperature in both °C and °F, average January temperature, and heating degree days (HDD).

Heat loss worksheet

The simple anaylsis I show here may be somewhat imprecise, but it accurately illustrates where the weak links are—invariably these are glazing and infiltration losses—and it will ensure you don't undersize your heater.

Building a greenhouse that has a tight envelope can have a dramatic effect on the heat loss of the space, and anything we can do to increase thermal resistance of the glazing at night will also be very beneficial.

Calculations

1. Determine the minimum extreme outdoor temperature (t_{out}, °F) in your climate's coldest month. Be sure to use to °F.

2. Choose the minimum allowable indoor temperature (t_{in}, °F) for your greenhouse based on your growing goals.

3. Calculate $(t_{in} - t_{out})$, the difference between minimum indoor and extreme minimum outdoor temperature. You will use this number for all the subsequent heat loss calculations.

4. In a table, like the worksheet in Table 7, write down the area (**A**, ft^2) and U-value (**U**, BTU/hr °F ft^2) of each surface of the greenhouse. Common U-values are in Table 5, or you can ask the manufacturer.

5. Now calculate the heat loss (BTU/hr) using the equation above for each element: $\mathbf{H = U \bullet A \bullet (t_{in} - t_{out})}$

6. Add the heat loss from each element, to get a subtotal, for example: $\mathbf{subtotal} = \mathbf{H_{walls} + H_{glazing} + H_{roof} + \ldots}$

7. Assume that infiltration losses are 25% of the total losses, so multiply the subtotal by 0.25 to get an estimate of infiltration.

8. Add the heat loss subtotal to the infiltration estimate to get the worst-case scenario heating needs. Use this number to choose an appropriate heater.

Greenhouse Element	Area (ft^2)	U-value (BTU/hr °F)	Heat Loss (Btu/hr)
Back wall			
Knee wall			
End walls			
Doors and windows in end walls			
Glazing			
Roof			
		Subtotal	
		Infiltration	
		TOTAL	

Table 7. Sample worksheet to calculate heat loss from the greenhouse

An example: Benefits of a thermal curtain

Here's an example from my own greenhouse in Calgary to show how the analysis works, and also to show how important thermal curtains can be to improve greenhouse performance.

Here in Calgary, the extreme annual low is about -40°F. Let's suppose my goal is to grow Mediterranean perennials and run an aquaponics system, so 41°F (5°C) is the minimum allowable indoor temperature. The difference between these temperatures, 81°F, is used in the calculation of heat loss through each component in Table 8.

Changing the target temperature, for example to 14°F (-10°C), reduces the heat loss overall—in this example, by one-third—but it does not change the relative losses of each component: Glazing (60%), Infiltration (25%), Walls (14%), Roof (4%), and Windows and Doors (2%).

Greenhouse Element	Area (ft^2)	U-value (BTU/hr °F)	Heat Loss (Btu/hr)
All four walls	331	0.04	1072
Roof	86	0.04	279
Door	18	0.07	102
Window	4	0.34	110
Glazing ***without*** curtain	170	***0.34***	***4682***
		Subtotal	**6245**
		Infiltration	**1561**
		TOTAL	***7806***

Table 8. I used the heat loss worksheet to calculate how my greenhouse might perform without a thermal curtain.

Adding a curtain

The effect of a curtain on heat loss is profound, as you can see in Table 9, even though the insulative value of the thermal curtain is very small—only about R3, or one-eighth the insulative value of the walls.

Overall, the curtain reduces total heat loss by about 30%, saving some 2400 BTUs. It also changes the relative losses between components: Glazing (43%), Infiltration (29%), Walls (20%), Roof (5%), and Windows and Doors (4%).

The other side of coin is that the curtain also increases the effectiveness of the thermal mass by 30%. That is, If you have a thermal mass that can keep the greenhouse charged for 12 hours with the curtain drawn, without the curtain this same mass will only keep the greenhouse warm for 8 hours.

Greenhouse Element	Area (ft^2)	U-value (BTU/hr °F)	Heat Loss (Btu/hr)
All four walls	331	0.04	1072
Roof	86	0.04	279
Door	18	0.07	102
Window	4	0.34	110
Glazing ***with*** curtain	170	***0.17***	***2341***
		Subtotal	**3904**
		Infiltration	**1561**
		TOTAL	***5465***

Table 9. I halved the U-value of the glazing to reflect the addition of a thermal curtain, reducing total heat loss by 30% compared to not using the curtain.

Thermal curtains are valuable even though my goals are only three-season growing and do not really include an aquaponics system.

In the shoulder season of spring and fall, curtains reduce fuel requirements—in my case, wood—lengthen the time the thermal mass stays "charged," allows greens and seedlings to be grown earlier and more quickly, and lengthens the growing season for hot climate plants like tomatoes, eggplants, and melons.

HEAT LOSS SOFTWARE SIMULATIONS

Verge Permaculture uses high-end thermodynamic modeling software that can predict how a building will perform before it is built, but this type of computer simulation is expensive and beyond the scope of this book.

Nevertheless, it may be something you consider. It uses a model of your design, heating degree days (HDD) for your climate, and information on the thermodynamic properties of the materials to predict how well the building will naturally ventilate without fans, how hot the space will get, how cold it will get without heat, and how much additional heat is required.

Computer models also allow us to optimize the design of subterranean heating and cooling systems, described later.

RESOURCES

- Build it Solar Heat Loss Resource: http://www.builditsolar.com/References/Calculators/HeatLoss/HeatLoss.htm
- Hot 2000: http://canmetenergy.nrcan.gc.ca/software-tools/hot2000/84

HEATERS AND INTEGRATED DESIGN

Once you've estimated your heat load, you can size a heater. Heaters can use natural gas, oil, wood, or electricity, and in North America they are usually specified in BTU/hr.

In the heat load analysis example of the last chapter, my greenhouse can expect to lose about 8000 BTU/hr in the worst-case scenario of the coldest night Calgary experiences, maintaing 5°C inside. A thermal curtain can reduce this to about 5500 BTU/hr.

To put this in perspective, a typical airtight stove will emit 45,000 to 75,000 BTU/hr. My greenhouse would quickly overheat if I used such a stove! That's why I'm a big fan of heaters like the rocket mass heater that emit heat into the space quickly, but also store excess heat in a thermal mass, such as a cob bench, to radiate out slowly over time.

Figure 15. The steel barrel of the rocket mass heater quickly radiates heat into the space while the cob bench stores excess heat.

Rocket Mass Heater

The small rocket mass heater in my greenhouse is enough to keep frost off the plants in the spring and fall, meeting my goal to extend the season.

The rocket mass heat is also very inexpensive to run since it uses waste wood I collect from the city. These stoves burn small diameter sticks very easily, so they integrate well with coppice systems—woodlots of trees that can be harvested frequently and continuously for narrow stems without killing the trees.

You can build one of these hot and highly efficient wood stoves with fire-bricks, cob, perlite (expanded rock used in gardens), recycled chimney pipes and, optionally, recycled barrels.

The rocket in my greenhouse burns sticks to heat a steel barrel that quickly warms the space before the hot air releases the rest of its heat into the cob bench.

Stay tuned, we are currently writing an e-book on how to size a rocket mass heater, as well as a coppice system to fuel it. We're also collecting data right now on subterranean heating and cooling systems, and will have an e-book out to guide people through the design and use of these systems.

Subterranean Heating and Cooling Systems

Also known as climate batteries by Jerome Osentowski, subterranean heating and cooling systems use small fans to blow air from the greenhouse through a network of underground plastic pipes.

The pipes are buried beneath the greenhouse in subsoil that is surrounded by insulation—underneath the subsoil as well as on the sides—creating a "thermal mass battery" for long term heat storage.

As hot air is circulated through the pipes in the summer, the air is cooled as the insulated subsoil takes in the heat. Later in the winter, cold air from the greenhouse is warmed by the insulated subsoil. Ultimately, this system can increase growing degree days by up to one-third without the use of heating appliances.

Integrated Design

The greatest benefits can be achieved by designs that integrate multiple elements to work together. It is unfortunate that this basic tenet is so frequently missed by our society, but the integration deficit is easily remedied with some creative thinking.

Integrated Design Ideas

- Aquaponics systems cycle water from fish ponds through planted containers, both fertilizing the plants and cleaning the water. The water is thermal mass and the fish provide more food.
- A wood-fired hot tub heats bathing water and the greenhouse, provides thermal mass and, as the water cools down, the greywater can be used for irrigation, emptying the tub and keeping it clean without chemicals.
- Better yet, harvest rainwater from the roof to refill the hot tub and irrigate.
- Similarly, a sauna in the greenhouse could provide thermal mass, heat, and relaxation.
- Don't underestimate the power of relaxation: make a sitting area in the greenhouse. My family often eats lunch in ours and, when I fire up the rocket mass heater in the winter, it's a good time to read a book and get away from the chaos in the home!

A WORD OF CAUTION

Not all integrated elements are beneficial, and some can be detrimental. For example, it's tempting to integrate livestock to benefit from their heat, but animal manure off-gases ammonia and can burn your plants. I would recommend against this kind of experiment.

If you do put in livestock, do not underestimate the power of ammonia if composting is not properly managed.

RESOURCES

- How we Designed our Solar Greenhouse: http://vergepermaculture.ca/blog/2011/01/09/how-we-designed-our-solar-greenhouse/
- Summer Greenhouse Update – Plus How We Would Design The Next One - http://vergepermaculture.ca/blog/2013/07/11/greenhouse-update
- Build it Solar: http://www.builditsolar.com/
- Solar Greenhouses, Chinese Style: http://www.energybulletin.net/node/52317
- Greenhouse design and installation: http://pennandcordsgarden.weebly.com/greenhouses.html
- Greenhouse design and installation: http://ceresgs.com/
- Three Legs of the Integrated Design Stool: http://vergepermaculture.ca/blog/2013/08/28/the-three-legs-of-the-integrated-design-stool/
- Heating the Greenhouse Rocket Style: http://vergepermaculture.ca/blog/2013/01/29/finishing-the-rocket-mass-heater/
- Rockets that Don't fly: http://vergepermaculture.ca/blog/2010/03/31/rockets-dont-fly/
- Rocket Stove Workshop, YouTube: https://www.youtube.com/watch?v=BoW-ICO83hM
- Subterranean heating and cooling: http://www.builditsolar.com/Projects/Sunspace/HighTunnelSolar/HighTunnelSolar.htm
- Keep an eye on our website for an e-book on how to size rocket mass heaters and coppice systems, and all things greenhosue and permaculture related: www.vergepermaculture.ca

A FINAL WORD

So, you've reached the end, and now it's time for action. I love passive solar greenhouses and I probably always will. They give respite from our long cold winters, extend our harvest, and give us a summer edge during Calgary's cold summer.

That said, these buildings are not perfect, and this strategy of extending our climate is just one of the thousand solutions. After using one for multiple years, I still see the need to garden outside as nature intended. In addition to outdoor annual gardening, I am a big fan of perennial crops and food forests. Sure, my climate limits what I can grow, but a variety of strategies are important to provide a diversity of yields.

Again, however, no solution is perfect. To varying degrees, greenhouses, food forests, and gardens are are all susceptible to pathogens, pests, hail, drought, frost, and more. But when we approach the challenge of growing our food with a diversity of methods, our chances of success increase dramatically.

The world needs gardeners and it needs us now. By many measures, agriculture is the most destructive force on the planet. It is also one of the most important and positive ways to reverse ecological degradation while taking care of ourselves and our communities.

We can change the world by force or by inspiration, and I choose the latter. I have found that people are really drawn to three and four-season greenhouses, and that they are a great way to get people interested in growing food again. Good luck on your greenhouse, and please send me a line with your projects and ideas.

Happy growing!

About the author

Rob Avis, a professional mechanical engineer, and his wife, Michelle Avis, cofounded Verge Permaculture to offer education and consulting to create sustainable human environments that work with nature.

Rob has studied environmental design around the world. His wealth of experience includes internships at the Permaculture Research Institute in Australia, studying renewable energy systems at the Nordic Folkecenter in Denmark, and off-the-beaten track travels throughout Mexico to examine sustainable agriculture practices. He has hands-on experience with natural building, low-energy homes, wind turbines, biological waste-water treatment, and broad-acre water harvesting.

Rob Avis

As a consultant, educator, and speaker for community events, non-profit groups, and businesses, Rob has been invited to guest lecture at the University of Calgary, taught workshops in partnership with Green Calgary, and to date he has taught the internationally recognized Permaculture Design Certificate to 300 students across Western Canada.

When Rob isn't teaching, consulting, or testing out new permaculture techniques, he spends his time with his children, Rowan and Naomi, playing guitar, and practising meditation.

Acknowledgements

This book came about with the support of a lot of amazing people.

My mother-in-law continues to allow and encourage all manner of experiments on her postage-size lot in Calgary.

Michelle, now the master of the greenhouse, produces more and more food out of our tiny backyard space every season.

Pioneers like Jerome Osentowski really pushed what is possible, and Gord Hiebert in Vernon, BC—www.elementecodesign.com—helped with our greenhouse design.

Through workshops and permablitzes, many people helped build the greenhouse and put in the rocket stove and bench, it was a pleasure to work with you all.

And thanks to my project manager, Alex Judd, and my editor, Andrew Bennett—the second edition is great.

My thanks to you all!

LIST OF FIGURES

Figure 1. The Solar Pathfinder is used to assess on site solar resources. www.solarpathfinder.com

Figure 2. Aspect ratios

Figure 3. Determine glazing angle and peak height. Illustration from The Solar Greenhouse Book, Rodale Press.

Figure 4. Determine roof slope, width, and wall heights. Illustration from The Solar Greenhouse Book, Rodale Press.

Figure 5. Typical large greenhouse shape and components

Figure 6. Raised "wicking" beds in the greenhouse

Figure 7. Ventilation louvre locations at the Central Rocky Mountain Permaculture Institute.

Figure 8. Fans can compensate for inadequate ventilation

Figure 9. The outline of the breakout door is visible below the chimney.

Figure 10. Plastic strips hung in doorways help to reduce heat exchange.

Figure 11. Slim line rain tanks use space efficiently to hold rain water for irrigation and thermal mass, but be cautious about freeze-thaw problems.

Figure 12. This gabion rock wall would be a great back wall: It uses vertical space, inexpensive rock, and it looks beautiful.

Figure 13. Tree Seedling trays being strapped together with pallet straps, and then assembled into an insulated footing for a yurt.

Figure 14. Seedling trays adapted to be ICF (Insulated Concrete Form) bricks, and then filled with concrete.

Figure 15. The steel barrel of the rocket mass heater quickly radiates heat into the space while the cob bench stores excess heat.

LIST OF TABLES

Table 1. Common roof pitches and their associated angle.
Table 2. Typical polycarbonate glazing materials and their thickness, R value, and transmissivity.
Table 3. Common materials used as thermal masses in greenhouses, and their associated heat capacities The larger the number, the more thermal energy a given mass can store.
Table 4. Typical insulation materials and their R-value per inch.
Table 5. Typical building components and their associated U and R values.
Table 6. Representative Canadian cities and their extreme minimum temperature in both °C and °F, average January temperature, and heating degree days (HDD).
Table 7. Sample worksheet to calculate heat loss from the greenhouse
Table 8. I used the heat loss worksheet to calculate how my greenhouse might perform without a thermal curtain.
Table 9. I halved the U-value of the glazing to reflect the addition of a thermal curtain, reducing total heat loss by 30% compared to not using the curtain.