## Introduction

The snow is shin deep, the mercury well below freezing. In the stunning clarity of winter sunshine, a complex triangle of glass rises from among the dazzling white drifts. A layer of condensation obscures the details of the verdant world inside, but as I draw closer, the green takes shape: a forest of kale, hanging baskets of alyssum, beguiling arch of pole beans. Hyacinths float atop vats of greenish water, as catfish swim in lazy circles.

In contrast with the cold, white world I just stepped out of, this winter landscape feels like paradise. As I quickly shed layers, my muscles release their frigid tension and my face relaxes into a smile. The air is humid, teeming with the sweet smell of soil, of respiring plants, of life.

> —Elise Hugus, "The Cape Cod Ark: A Study in Self-Sufficiency," *Edible Cape Cod* Winter, 2014.

In the winter of 2011, I went out to see a bizarre-looking structure on a farm in East Boulder, Colorado. The building was a prototype net-zeroenergy greenhouse funded by the Colorado Department of Agriculture, but except for some glass, it bore little resemblance to a greenhouse. Wood boards, acting as light reflectors, protruded from the front. A sharply peaked sawtooth roof reflected light down to the plants inside. Moveable boards of insulation opened and lowered between panes of windows.

Standing in the humid room teeming with vegetables, I saw a spectacled man shuffling along the wall. He occasionally stopped to plug in his Macbook into various gadgets. "He's just getting data," the tour guide explained with a wave. It was a brief moment but one I remember well—as a marker when life took a different direction.

The data-collecting gentleman was Marc Plinke, who would turn out to be my business partner and co-author. In a follow-up meeting over coffee, we discussed the experimental greenhouse, the potential for the design and technology, and future business aspirations. We were in the same mindset, and a few months later we started a business to test and refine the concepts and make energy-efficient, sustainable greenhouses available to a wider market. We named it *Ceres Greenhouse Solutions* after the Roman goddess of agriculture, inspired by an image of an unrulyhaired goddess I saw a few months earlier on European currency. As a business, Ceres has provided an incredible vehicle in which to research and apply new ideas to net-zero-energy greenhouses. It has been an incubator that allowed us to tweak and improve designs with every iteration, exploring and developing new ways to store and transfer the heat of a greenhouse.

Much of our development effort went into a type of ground-to-air heat exchanger we call a *Ground-to-Air Heat Transfer* (GAHT) system, which stores excess daytime heat from the greenhouse in the soil underground. We've worked to simplify the GAHT system, making it more cost-effective and easy to install and recorded huge quantities of data to improve their efficiency. We've designed and installed hundreds of GAHT systems all over the world (from Sweden to Brunei), in growing operations large and small, demonstrating the universal applicability of the system.

We also design and build greenhouses themselves, concentrating on well-insulated structures for growers in harsh climates where the growing season is limited to a few frost-free weeks. Our primary greenhouse design is a shed-style structure with a polycarbonate roof and glass view windows or polycarbonate walls. (The specifics of glazing, angles, dimensions, etc. are customized to meet the grower's needs and location.)

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This arrangement works well to maximize year-round light and retain heat for harsh climates.

The design is efficient, attractive and cost-effective for a range of growers. We've had the opportunity to work with backyard gardeners, schools, farms and high-tech commercial greenhouses. The potential for year-round, sustainable growing environments spans all these sectors — plus retirement homes, office buildings, prisons, hospitals...wherever there is space and a need for food.

#### **Our Approach**

An internet search for "greenhouse" yields an array of companies that have "the best" greenhouse design. The best materials, light transmission, durability...whatever it is, many claim to have the sole superior greenhouse. Hopefully, you already know to take these statements with a grain of salt. The truth is there is no one "right" greenhouse design; the best greenhouse for you depends on your climate, your goals, and your budget. Texas has a very different climate than Maine. Both can have highly functional, energy-efficient greenhouses, but they require different solutions.

A solar greenhouse is a particular type of greenhouse. It relies on a tailored approach for the creation of a structure that works with the local climate and resources, using the sun as the predominant energy source not only for growth but for the structure's energy needs. The aim of this book is to explain the array of options available for designing and building abundant, year-round greenhouses. Moreover, it serves to provide an explanation of the fundamental concepts that allow solar greenhouses to work, so that you can navigate the choices out there and find an approach that is truly right for your situation.

The current literature on solar greenhouses consists of books that are either very dated (from the 1970s) or that describe a very specific building method that the author has adopted. You can find a book on building a greenhouse out of recycled tires, or with a Chinese design, or underground. We wanted to create a resource that fairly compares and contrasts all these approaches, and explains the fundamental concepts behind them, so that you can go on to create a year-round oasis that is truly right for you.

By choosing to look at the fuller picture, we can't explain the details of each system, such as how to build a build a rocket mass heater or install a solar panel system. These topics deserve in-depth discussion, but we could not write a tome and had to draw lines somewhere. Thus, we provide an overview of systems and building methods, and conclude most chapters with recommendations for further reading. We did not have the space to provide step-by-step building instructions for every construction type, but provide the resources that do, so you can go on to take the next step.

Solar greenhouse design is unique in that it stands at the intersection of simple, time-tested methods and advanced technologies. Heating methods can be a few drums of water or an intricate solar hot water system. The range of technology makes costs for energy-efficient greenhouses extremely wide-ranging, from less than \$1 per square foot to over \$100. We provide ballpark figures in order to help you make decisions, but leave the final budgeting work to you, recognizing that costs vary greatly by location and are always changing.

#### How This Book Is Structured

The book begins with the big picture: what is a solar greenhouse and where does it fit in in the range of growing options? It ends with the final step of the design process, how to integrate different growing methods and laying out the greenhouse floor and planting plan.

The heart of this book lies in the middle two sections. Section 2 explains the fundamentals of solar greenhouse design. It concentrates on the greenhouse structure—the glazing, insulation, ventilation, overall design, and construction options. Section 3 describes the range of sustainable heating and cooling options for greenhouses. These methods span active (electric) and passive methods, and range in complexity. Most focus on ways to store the excess heat during the day in the greenhouse for use as heating at night, allowing the greenhouse to

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become "self-heating," a phrase we often use to differentiate our design philosophy from more petroleum-dependent approaches. The greenhouse, abiding by the greenhouse effect, creates all the heat needed. The "heating and cooling systems" we describe merely transfer that heat in simple and elegant ways.

Every chapter in this book includes examples of successful solar greenhouse projects. Designed by researchers, experts, backyard tinkerers and home growers, these examples are meant to exapnd the possibilities, while highlighting a unique system or design feature. Perhaps it's a rocket mass heater combined with a hot tub, or a solar hot water system integrated with an aquaponics greenhouse. The short profiles of successful greenhouses aim to inspire and guide you in creating a productive, year-round greenhouse unique to you.

### Acknowledgments

Writing a book can be an arduous, often stressful task. Fortunately, I had many people who made the road easier, contributing their time, ideas and expertise. Thank you to the numerous growers, experimenters, researchers and backyard innovators who contributed to this book by sharing their experiences and photos. Moreover, it is through their work and those like them, that solar greenhouse design is what it is today. In particular, thank you to these innovators:

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# THE BIG PICTURE

## **CHAPTER 1**

## What Is a Solar Greenhouse?

"Don't all greenhouses use the sun?" "You mean a greenhouse with solar panels?"

Stand in front of a sign that says "Solar Greenhouses" at a green products trade show, and you'll frequently be asked these questions. Few people are familiar with the concept of a solar greenhouse. Simply put, it's a greenhouse that uses the sun's energy not only for growth, but also for passive heating; thus, it is able to maintain suitable growing temperatures without reliance on fossil fuels.

Indeed, all greenhouses use the sun for heat and growth *during the day*. At night, most greenhouses quickly lose all that heat due to the poor insulating quality of their materials. On a winter morning, a standard unheated greenhouse usually is only a few degrees warmer (if at all) than the outdoor temperature. Moreover, unless it is ventilated or artificially cooled, a standard greenhouse traps so much heat during the day that it will drastically overheat.

Energy author Dan Chiras once used an excellent analogy to give a quick picture of traditional greenhouses: Imagine living in a tent.<sup>1</sup> When it's 90°F (32°C) outside, sitting in a closed tent is the last place you want to be. When it's 32°F (0°C), sitting unprotected in a closed tent is also uncomfortable. A tent offers very limited protection and insulation. Traditional greenhouses work similarly for plants; they overheat during the day if uncontrolled, and then they let all that heat out at night. The result is wild temperature swings that stress or kill plants. To compensate, greenhouse growers often blast the greenhouse with heating and cooling systems in order to grow year-round.

The reason for these inefficiencies has to do with some basic principles of design. Traditional greenhouse design focuses on maximizing light by maximizing glazing. (Glazing is a term for any light-transmitting material, like glass or clear plastic.) Traditional greenhouses are normally "100% glazed," meaning all surfaces are made of clear or translucent materials. While they are good at letting in light, glazing materials are extremely poor at retaining heat. You've experienced this first-hand if you've ever sat next to a window on a cold night—it's a chilly spot. Now imagine an entire building made out of windows. It naturally gets very cold if not heated through the winter.

Solar greenhouse designs takes a different approach. Instead of creating a fully glazed structure, it finds a balance between glazing and insulation in order to create a more thermally stable structure (one that naturally resists overheating and overcooling). Designers use glazing *strategically*, placing and angling it to maximize light while reducing the glazing area as much as possible to minimize heat loss. Furthermore, solar greenhouse design emphasizes *storing* the excess heat of the greenhouse during the day and using it for heating at night. Instead of ventilating excess heat outside, only to have to re-heat the structure at night, solar greenhouses rely on the simple greenhouse effect for heating—using the heat from the sun that is collected and trapped in the greenhouse during the day. Instead of fossil fuels, the sun provides the energy; the greenhouse collects and stores that energy, providing its own heating when it's required.

#### The Many Meanings of Solar

The word "solar" is an incredibly broad term—meaning relating to the sun—but it conjures up some specific images. When most people hear "solar," they picture a building with solar photovoltaic (PV) panels.

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Greenhouses can include solar panels to generate renewable electricity; however, a much wiser use of the sun's energy for heating is through *passive solar design*: the practice of using solar energy for heating without relying on any electrical or mechanical devices. Specifically, it advocates carefully enhancing solar gain and minimizing heat loss in order to reduce or eliminate the dependence on fossil-fuel-based heating/cooling.

Though passive solar heating does not use electricity, in can be applied to buildings that do. Today in the building industry, a passive solar home generally refers to a house that utilizes passive solar design. These homes usually still have electrical appliances, like a refrigerator or washing machine. Similarly, solar greenhouses rely on passive solar heating, but they often have some electrical components. Many of these electrical systems transfer heat from the greenhouse to a storage medium, like the soil or water, allowing the greenhouse to take full advantage of the powerful greenhouse effect. The term *passive solar greenhouse* is often used to more explicitly describe a greenhouse that uses passive solar heating and has no electrical components at all—so it uses no electricity.

As you can see, there are some overlapping terms, so we should clarify: In this book we use the word *passive* on its own to describe systems that don't use electricity. *Active* is shorthand for systems that require electricity, like fans or pumps. For us, "solar greenhouses" are those that rely on passive solar design, and can be electrical or nonelectrical structures.

#### The Seven Principles of Solar Greenhouse Design

Solar greenhouses vary in almost every way—their shapes, styles, sizes, building methods, and technologies. However, there are a few unifying elements that apply to them all. To put them in a nutshell (because every book needs a nutshell), we've distilled them into these seven best practices:

1. **Orient the greenhouse toward the sun.** In the Northern Hemisphere, the majority of the glazing should face south to maximize exposure to light and solar energy.

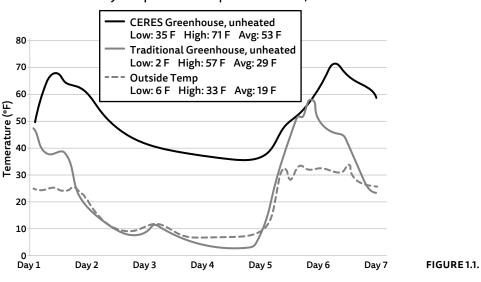
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- 2. **Insulate areas that don't collect a lot of light.** In the Northern Hemisphere, the north wall of the greenhouse plays a minor role in light collection. It should be insulated in order to reduce heat loss, creating a more thermally stable structure.
- 3. **Insulate underground.** Insulating around the perimeter of the greenhouse allows the soil underneath it to stay warmer, creating a "thermal bubble" underneath the structure that helps stabilize temperature swings.
- 4. Maximize light and heat in the winter. To grow year-round without dependence on artificial lights or heaters, it is crucial to maximize naturally occurring light and heat during the colder months. This is done by using proper glazing materials and angling the glazing for winter light collection—in general, using the glazing area strategically.
- 5. **Reduce light and heat in the summer.** Growing during the warmer months can create problems with overheating. Strategic shading, glazing placement and angles reduce unnecessary light and heat in the summer.
- 6. Use thermal mass (or other thermal storage techniques). Thermal mass materials are materials that store the excess heat in the greenhouse during the day and slowly radiate it at night or when needed. This evens out temperature swings, creating a more controlled environment for growing. Almost all solar greenhouses have some mechanism to store heat, broadly called thermal storage.
- 7. Ensure sufficient ventilation. Natural ventilation ensures a healthy plant environment and controls overheating.

## The Case for Solar Greenhouses

Fig. 1.1 shows the temperatures in two unheated greenhouses over a few cold, winter days in Boulder, Colorado. The first is an uninsulated greenhouse, made out of a PVC frame and polyethylene plastic. The second is an insulated solar greenhouse designed with the principles listed above.

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Daily Temperature Comparison Boulder, CO

The standard greenhouse drops to a low of  $2^{\circ}F(-17^{\circ}C)$ ; the solar greenhouse stays above freezing.

Solar greenhouses are often described using nebulous terms like *high-performance* or *energy-efficient*, but this is what it simply comes down to: they are able to stay much warmer year-round, and thereby grow much more than conventional greenhouses—without relying on fossil-fuel heating. They also overheat less, because they do not have excessive areas of glazing. Hence, they maintain a more stable growing environment, conducive for plants and able to grow year-round, even in harsh environments.

We've addressed the top two most common questions about solar greenhouses, now let's address a third: Do they get enough light? People often note that solar greenhouses look more like sunrooms or sheds than greenhouses. Indeed, they usually have less glazing because they work by balancing the glazed area with insulation for efficiency. However, contrary to what you might expect, they still receive roughly equivalent or even greater light levels than conventional structures. This

has to do with the directional nature of sunlight and the placement of glazing, a topic discussed in Chapter 5. When light enters a solar greenhouse, rather than being transmitted through the north wall, it is reflected back inside by an insulated north wall (usually painted white).

The effectiveness and production potential of solar greenhouses has been documented in research trials—and thousands of backyards—for decades. Notably, in the early 1970s, The Brace Institute at McGill University conducted a unique side-by-side study comparing a conventional greenhouse with one built according to solar design principles. Made out of double-layer polyethylene plastic on all sides, the conventional greenhouse served as the control. The experimental solar greenhouse, called the Brace greenhouse, featured an insulated north wall, a double-layer plastic south wall and several other efficiency features. Both operated over a few seasons, and key data—temperatures, light levels and yields—were recorded. The Brace study found that light levels inside the solar greenhouse during the winter were comparable to the fully glazed structures. They were high enough to grow as much or more than conventional structures.

Here are some of their key findings:

- "The new design has yielded significant savings in energy requirements, of up to <sup>1</sup>/<sub>3</sub>, compared to the conventional greenhouse."
- "Total weight of fruit produced in the Brace greenhouse was three times that produced in the control greenhouse."
- "Frost does not occur in the Brace greenhouse until one month after frost had destroyed the crops in the standard greenhouse."<sup>2</sup>

#### The Need for Solar Greenhouses

The greenhouses referred to in Fig. 1.1 were both residential structures; however, commercial greenhouses encounter the same problems. Typically, energy costs are the third largest expense for commercial greenhouse growers in the US (behind labor and plant materials). As of 2011, 70% to 80% of energy costs went to heating the greenhouse through cold North American winters.<sup>3</sup> Moreover, because of the inherent inefficiency of most greenhouses, these energy costs are vastly greater

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than for other types of buildings, making it challenging to grow yearround profitably. For instance, currently, the heating/cooling costs for commercial year-round greenhouses in Colorado are \$3–4 per sq. ft.<sup>4</sup> In comparison, the heating/cooling costs for an average Colorado home are between \$0.10 to \$0.50 per sq. ft.<sup>5</sup>

As a backdrop to this situation, our agricultural system is precariously dependent on fossil fuels. For every calorie of food on your table, it took an average of *ten* calories of fossil-fuel energy to produce it. Every step of the food production chain relies on fossil fuels, from growing (pesticides and fertilizers), to processing (emulsifiers, additives, preservatives), packaging (plastic containers), and transportation. For many fruits and vegetables, shipping increases the 10:1 ratio of "energy in" to "energy out." For example, "97 calories of transport energy are needed to import one calorie of asparagus by plane from Chile [to the UK], and 66 units of energy are consumed when flying one unit of carrot energy from South Africa."<sup>6</sup>

Combined with volatile oil prices, finite oil supplies, and a warming planet, these statistics present a grim picture. Greenhouses are just one of many solutions that reduce the energy dependence of our food supply and re-localize food production. However, the current design of greenhouses has the potential to only shift the problem, not solve it. Though many greenhouses provide local crops, the inefficiency of the structures can undermine the effort. For example, a study conducted by Cornell University compared the total energy needed for growing tomatoes in greenhouses in New York for local markets versus growing tomatoes in fields in Florida and shipping them to New York. Taking into account production and transportation, tomatoes grown in standard greenhouses used about six times more energy than the shipped tomatoes. Though greenhouses created a local food supply, they increased the total demand for fossil fuels.<sup>7</sup>

Solar greenhouses hold tremendous potential as a way to reduce both food miles and fossil-fuel use, for commercial and home growers alike. The nature of solar greenhouses as warm year-round structures enables backyard gardeners to grow crops (like bananas, mangoes, Many farmers are interested in greenhouses; what scares them the most are the heating bills.

—Steve Newman, Colorado State University, Greenhouse Extension

avocados and vanilla) that are normally shipped thousands of miles across oceans. Unlike conventional greenhouses, which often struggle to stay above freezing, solar greenhouses greatly expand what we can grow, in any climate by harnessing the sun.

#### Endnotes

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