Introduction

By means of microscopic observation and astronomical projection
the lotus flower can become the foundation for an entire theory of the universe
and an agent whereby we may perceive Truth.

— Yukio Mishima

A Case for Building Science

WHY DO WE NEED BUILDING SCIENCE? We've been building shelter just fine, all around the world and throughout time, without quantifying the physics of heat and moisture movement. Safe shelter is a birthright to all, and the potential to design, to build, to create, exists within each of us. Doesn't all this complicated building science just get between us and the work, complicate things and distract us from our intuition?

So, why do we need building science? Because our buildings have grown increasingly complex, and we expect very high levels

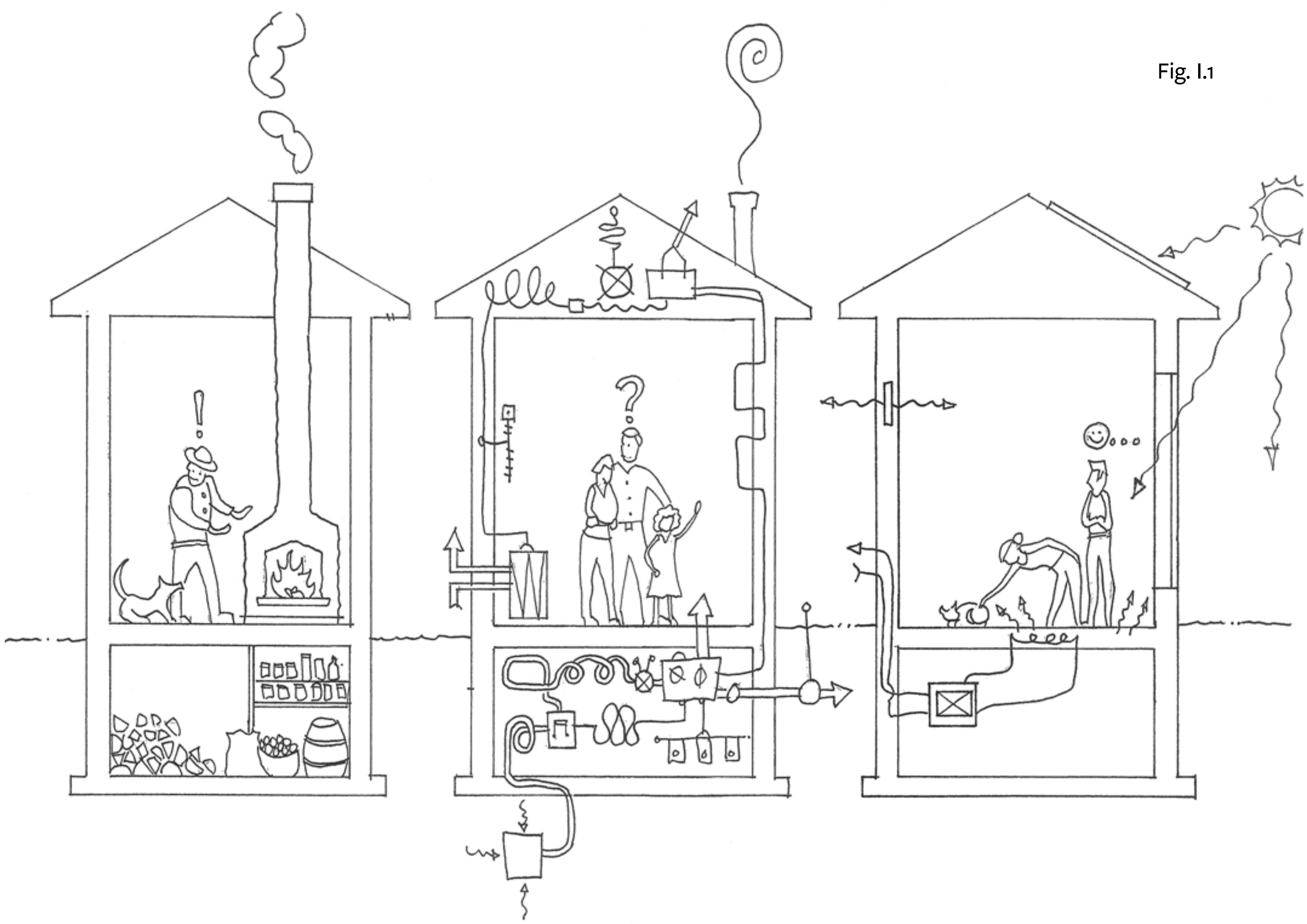


Fig. I.1

of comfort from them. Many of the biggest problems we have with our homes arise from problems with how our buildings manage heat and moisture. Much of the housing stock in North America is plagued by significant moisture problems (rot and mold), poor indoor air quality, and exorbitant energy loads, leading to great expense — for both the climate and for owners. We ask a lot of our buildings in terms of interior climate control, comfort, healthy space, and good durability, and in pursuit of these goals we burn a lot of carbon and use a lot of toxic materials. We need the tools and understanding afforded to us by the practice of applied building science to understand these problems better, so we can choose solutions that will create buildings that meet our needs without enacting such a heavy toll on the planet's well-being.

Fig. I.2: *A return to time-tested natural materials is a consequence of many years of building with toxic materials.* Credit: Ace McArleton — New Frameworks Natural Design/ Build.

Some of these solutions are old. We have been building with low-impact materials such as wood, stone, earth, lime, and straw for thousands of years. After nearly a century of building with whatever (possibly toxic) materials manufacturers were offering, many people now demand healthy homes built with low-toxic materials that provide high levels of efficiency with low carbon footprints. Those time-tested natural materials we built with for all those pre-Industrial Revolution years are more relevant than ever. To adapt them into this new context, we need to apply building science principles to ensure we use these natural materials effectively to create durable, high-performance homes.

Some of these solutions are new. So, we need to be able to predict how a building might perform before taking risks and trying new things. We can never really know, of course, until a building has been up for a few decades — but we need to know enough to manage risk and innovate appropriately. We need to have some benchmarks and goals to know if the new things we try are indeed working.

Most of all, we need building science because we need to elevate the bar of quality for our built environment, not just incrementally, but significantly and quickly, to address the critical issues of climate destabilization, unsafe and insecure housing, "sick" buildings, and housing that costs too much to operate. We can use what we have learned through observation and experimentation with heat, moisture, and materials, and by referencing patterns that have surfaced in thousands of buildings over the last few hundred years to dramatically improve the durability, safety, comfort, cost, and impact of our buildings. While it is far from the only discipline involved in creating the built environment, building science has to play a critical role if we want to achieve the lofty goals we have set for ourselves.

Building Science: A Very Brief History

Humans are innate scientists — or at least, there are a few in every crowd. A true survey of the applied practice of building science, across cultures and throughout the ages, would make for a fascinating read. Here in North America, we have been building wood-framed and masonry (earth, brick, stone) homes for the last few hundred years. Most have been lost to the ravages of time, but many have endured. Homes built of solid wood (i.e., logs, planks) and earth were very durable and quite comfortable. As structural engineering advanced, and we began building lighter structures out of smaller things (wood studs, steel, glass), our houses became less comfortable as we lost the thermal properties and tightness of those solid earth and wood walls. Around the 1920s and 1930s, we decided as an industry that insulation in our buildings was a good idea and worthy of bringing to market.

It took only a short decade or two before we began to see the first signs of moisture damage — paint began to peel from the siding. The prevailing hypothesis: vapor was moving through the walls from the inside, pushing through the wood siding, and driving the oil-based paint off the wood. The proposal, codified in building codes for decades to come: a vapor barrier to be installed on the inside of the building, stopping the vapor before it could move into the wall. The result: the continuation of vapor-related damage on both exterior and interior wall surfaces. The diagnosis was correct, but as we will learn, simply putting up a vapor barrier does not take into account the full cycle of vapor movement in our

Fig. I.3: *Building physics is at play whether we understand it or not — the penalty for ignoring the physics can be severe!* Credit: Top and bottom right: New Frameworks Natural Design/Build.

buildings; therefore, it is not in and of itself a suitable cure to the problem. A systems-level solution is needed for a systems-level problem.

In the 1970s, the United States and Canada experienced dramatic increases in fuel prices, resulting in energy improvement measures across all sectors of the economy, including buildings. We developed diagnostic technology, like the blower door, to be able to understand how air leaks occur in our buildings, and we dramatically increased the amount of insulation in our walls and roofs. New materials were employed; new innovations were brought to the market.

Again, we began to see moisture damage: rotting roofs, sheathing, siding, and framing. Over the decades to follow, we have steadily been learning what we can and cannot get away with in our buildings — as the invisible worlds of heat and vapor are made visible through the observations of how our buildings hold up, and what patterns of failure emerge. When we add more insulation, walls get colder and stay wet longer. Some materials seem to hold up when they get wet, and others fail quickly. For those of you new to the high-performance building world, it is worth noting that few of the strategies we will present are new — we have been building super-insulated, airtight, low-load, passive solar-heated buildings successfully (and not so successfully) for over 40 years. It is on the shoulders of the giants who raised these buildings that we stand, and the presentation of the information in this book is possible only because of the curiosity, leadership, fearlessness, and innovation of the designers, builders, engineers, and owners before us who were committed to learning what they could in pursuit of building better buildings.

Fig. I.4: *Proof of concept for high performance/ passive solar construction was established in 1939 with groundbreaking homes such as Keck and Keck's first known "solar home" in Glenview, IL.* Credit: Nicole Serradimigni — VHT Studios.

How to Use This Book

When I started designing and building my house in 2000, having neither practical nor academic experience, I was compelled to learn as much as possible as quickly as possible. Further complicating matters was my choice to build with timbers, straw bales, and earthen plaster, about which little was known and much was misunderstood, particularly in the context of the cold, wet climate of the northern Vermont mountains. Having seen how quickly moisture can break down a conventional building, and knowing what a bad reputation building with earth and straw had in my region, I wanted to know all I could about how these materials worked with moisture and, as an assembly, how these walls performed in more extreme climates. Fortunately, I was able to draw upon work from researchers such as Dr. John Straube and Don Fugler, engineers such as Marc Rosenbaum and Bruce King, and builders such as Paul Lacinski and Chris Magwood (and many others), who had already started to develop some regional best practices based on fundamental building science principles.

This book is intended to be the resource I wish I had when I started this journey, and it is written with the motivated or curious homeowner, aspirational or active owner-builder, and developing or practicing builder or architect in mind. This book serves as a foundational approach to applied building science — the essential rationale, physics principles, and strategies for building a high-performance home. The focus is restricted to energy and moisture, although related topics such as structure, acoustics, and lighting are referenced throughout the book.

This book won't tell you everything you need to know about how to build a high-performance

Fig. I.5: *Thanks to our ever-growing understanding of how buildings work and respond to their environments, today we are designing and building some of the best-performing homes that have ever existed.*
Credit: Top and bottom: Ace McArleton — New Frameworks Natural Design/Build.

house. It will, however, lay out a systems-based approach to developing critical thinking that you can apply to your home. This book will arm you with the information and strategies necessary to think your way through decisions regarding materials, assemblies, and mechanical systems, and it will help identify the areas of further study or greater expertise that may be required to make good decisions. Finally, this book will create a framework for asking better questions, which in time and with practice lead to better answers, and ultimately to better buildings.

Part I:

Rationale

Credit: New Frameworks Natural Design/Build.

Chapter 1

Establishing Goals

Before we dive into the theory, strategies, and details of how to manage heat and moisture in our buildings, it is critical that we begin by establishing the values and goals for our building projects, knowing that every project, with different stakeholders and serving specific purposes, will have a unique composition of values and goals. Why is this so important? After all, the physics are the same; heat and moisture don't change based on your proclivities. The importance lies in being able to ensure that the many decisions you will have to make in response to the guidelines presented in this book all lead toward a result that matches your original intentions. This is not something unique to building science — this is an important approach for any project. It is all too easy to think that there is a "right way" from a building science perspective, that just needs to be identified. Rather, the information concerning the performance of our buildings can be used in support of our goals — or it can lead us away from them if we haven't done a good job of setting clear objectives.

There are many definitions and graphical flowcharts representing this process. Here is a simple structure that runs through the exercise with a few basic examples:

Identify Values

First, what values motivate this project and what are your priorities? It is very important to note that you will have values that will conflict with each other; you will have to assign a hierarchy of importance to them. The more time you can spend getting clear about your priorities (and practicing how to communicate them clearly to others), the easier it will be to make decisions to resolve inherent conflicts — many of which inevitably involve cost — when they surface.

Define Goals

Next, what are the specific goals and results you are working toward? The goals should reflect your values. Set these goals early in the design process to guide the strategies and details.

Fig. 1.1

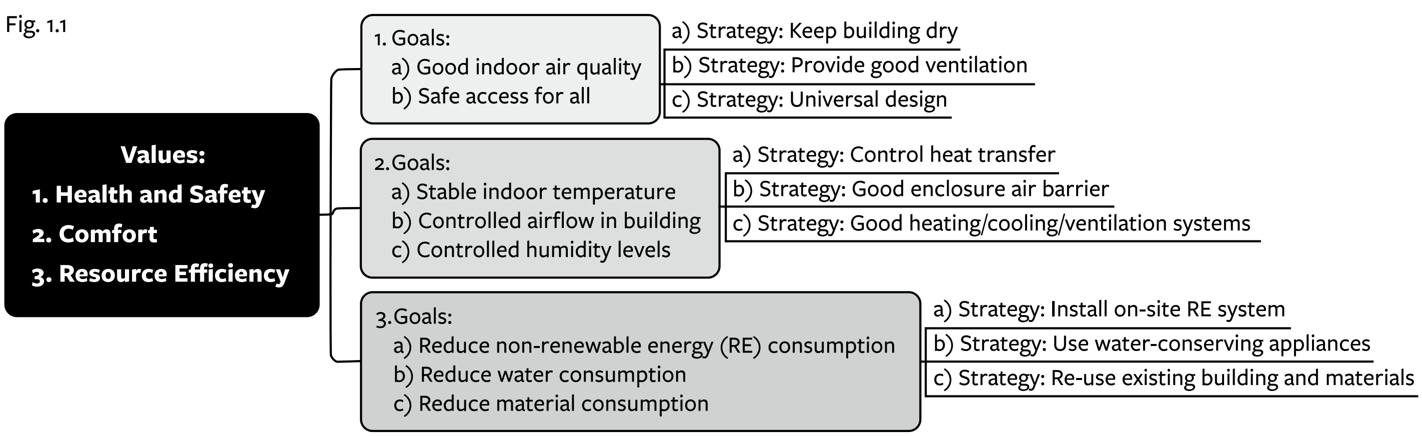


Table 1.1

Value: Health and Safety	
Goal: Good indoor air quality	
Strategies	***Actions***
Keep building dry (avoid mold)	Follow moisture control strategies to create a well-detailed enclosure that avoids leaks, condensation, and groundwater intrusion.
Good ventilation	Install a well-sized and appropriately designed ventilation system for the home, and ensure it runs correctly.
Reduce pollutants	Avoid products with off-gassing chemicals such as the solvents and glues common in paints, floor covering, and furnishings.
Combustion safety	Avoid the use of combustion appliances and/or use sealed combustion appliances when necessary.
Goal: Safe Use for All	
Universal Design (UD)	Follow established UD guidelines to ensure access to those needing assistance moving about in the home.

Table 1.2

Value: Comfort	
Goal: Stable indoor temperature	
Strategies	***Actions***
Control heat transfer	Follow thermal control strategies for a well-detailed, airtight and well-insulated enclosure, and include thermal mass inside the building.
Provide appropriate heating and cooling	Install a well-sized and appropriately designed heating/AC system for the home, and ensure it runs correctly and is serviceable.
Keep surface temperatures warm	Insulate slabs, walls, and ceilings. Install thermally efficient windows.
Goal: Controlled air flow (no drafts when cold, circulation when warm)	
Install quality air barrier	Ensure air barrier detailing in design, and perform quality control in the field with a blower-door test.
Good ventilation	Install a well-sized and appropriately designed ventilation system for the home, and ensure it runs correctly.
Goal: Controlled humidity levels	
Same as for other goals addressing comfort	Keep building dry, keep surfaces warm, install an appropriate ventilation system.

Setting measurable targets will make it easier to identify strategies and understand the results. Examples might include wanting a net zero energy home, or avoiding the use of any of the materials on the "Living Building Challenge Red List."

Develop Strategies

How can you reach your goals? You will need to decide on the steps and solutions that are likely to give you the results you seek. The strategies laid out in this book that support good moisture and thermal control may be valid unto themselves, but depending on the other goals you have set for this building, some of these strategies will be highly relevant, and others less so.

This is a deeply personal exercise, whether for owners or for professionals. The more intention you can bring to this process, the more likely it is that the final project will reflect your values, reach your goals, and employ successful strategies. In the world of high-performance building, common priorities emerge; some of these appear in the list below to help you seed the process of establishing your own building priorities.

Health and Safety

While this may seem like an obvious standard for all buildings, it is quite clear from the preponderance of newly constructed homes with terrible indoor air quality (IAQ) that this is not a universally held priority.

Comfort

Comfort is driven by humidity and temperature. Temperature here is not just air temperature, but *operative temperature,* which is a weighted average of air temperature, surface temperatures of a space, and air velocity. In high-performance homes, good insulation keeps surface temperatures closer to air temperatures, enhancing comfort.[1]

Durability

This is a priority often taken for granted, but rarely understood, thus keeping the renovation industry employed for the foreseeable future. We explore strategies for moisture durability in depth in this book — this is perhaps the governing focus of building science. One of the crucial questions to answer is this: "How to we keep our buildings really comfortable using little energy and without them rotting prematurely?"

Resource Efficiency

Resource inputs into the building — materials, water and energy — must be managed to achieve goals relating to affordability, independence, resiliency, and ecological and social responsibility — this is one priority that can unite people across the political spectrum!

Fig. 1.2: *Sweating windows can be caused by poor quality windows, elevated indoor humidity levels, or a combination of the two. They are a sign that the building's durability may be compromised in other parts of the enclosure as well.* Credit: New Frameworks Natural Design/Build.

Table 1.3

Value: Durability	
Goal: Keep rain and snow from getting in	
Strategies	***Actions***
Control bulk water entry	Follow moisture-control strategies of a well-detailed enclosure, avoiding leaks and groundwater intrusion.
Control surface water	Install storm water control (i.e., gutters) that integrates with a well-drained site.
Goal: Keep condensation out of the enclosure	
Install quality air barrier	Ensure air barrier detailing in design, and perform quality control in the field with a blower-door test.
Appropriate ventilation system	Install a well-sized and appropriately designed ventilation system for the home, and ensure it runs correctly.

Table 1.4

Value: Resource Efficiency	
Goal: Reduce non-renewable energy consumption	
Strategies	***Actions***
Control heat transfer	Follow thermal control strategies of a well-detailed air-tight and well-insulated enclosure, avoiding thermal bridging.
Provide appropriate heating and cooling	Install a well-sized and appropriately designed heating/AC system for the home, and ensure it runs correctly and is serviceable.
Install renewable energy systems	Install solar electric or thermal panels; use biomass for solid-fuel heating.
Goal: Reduce water consumption	
Use water-conserving appliances	Install low-flow faucets, showerheads, and toilets, and service regularly to eliminate leaks.
Integrate water-conserving systems	Design for rainwater catchment, greywater recycling, and composting toilet systems.
Goal: Reduce material consumption	
Re-use existing buildings and materials	Rehab existing buildings when possible; salvage what must be demolished; purchase quality used materials when possible.
Use low-impact materials	Use natural and regionally sourced abundant materials such as stone, wood, straw/hemp; select products with high recycled content (everything from steel beams to cellulose insulation).

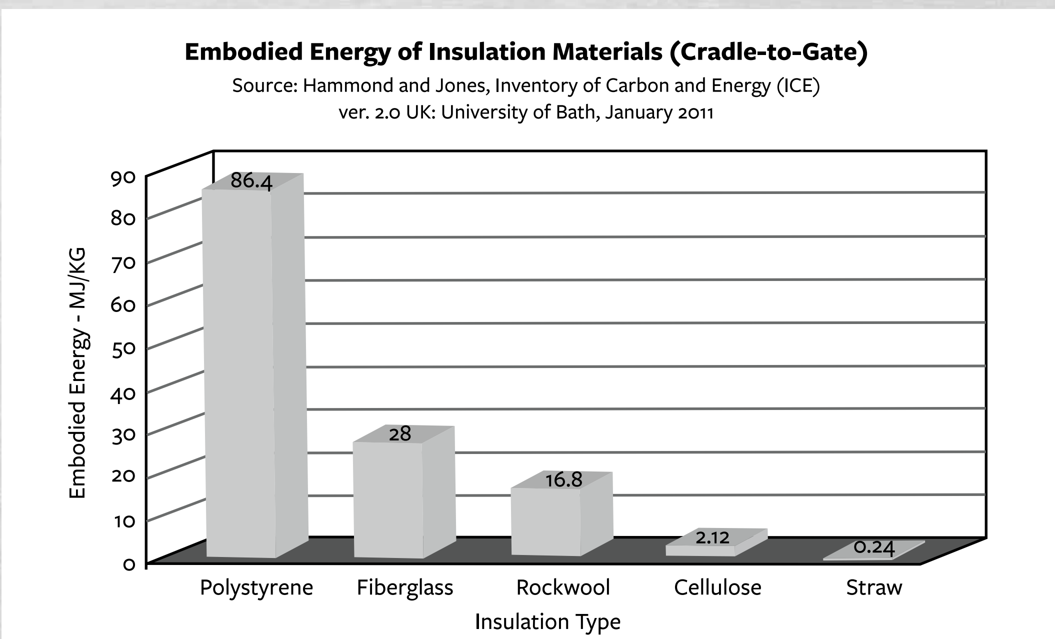
Embodied Carbon and Operational Carbon

There is a particular urgency regarding the climate impact of our buildings. At the time of this writing, 97% of the science community has come to consensus about the fact that anthropogenic (human-caused) greenhouse gas emissions will lead to irreversible climate disruption if dramatic reductions are not realized within the first few decades of this century.[2] In order to address this emergency, Architecture 2030, a leader in the climate action movement in the building industry, has called for zero carbon emissions by 2050 for all new construction. This includes both *operational carbon,* which is the carbon load created by the use of energy to heat and power a building, as well as *embodied carbon,* which is the carbon that is released in the manufacturing, production, and transportation of our building materials.[3]

For the decades that the building community has been working on improving energy efficiency, the strategy has been to use relatively high-embodied carbon materials, such as insulation, to offset long-term operational carbon loads, which over the life of the building are considerably greater (especially for conventional buildings). However, this is changing rapidly, and the building community must now take the consideration of embodied carbon very seriously, for the following reasons:

- Within the short time frame we have to reduce impacts, using high-embodied-carbon insulation to reach high levels of building energy performance, especially spray and board foam, may not save enough energy to justify its use (as compared to building a lower-performance building). No longer can we "front-load" 20 or 30 years' worth of operational carbon into the construction of our buildings and wait for the long-term reductions to kick in — we need immediate reductions, which must come from the construction phase, particularly in material selection.
- As we build buildings with lower and lower operational loads, a higher percentage of our carbon impact is in our materials. We know how to improve energy efficiency, but we must focus on how to do it using lower-carbon →

Fig. 1.3



materials and practices. "Net Zero" and other approaches using renewable energy to offset operational carbon does nothing to offset our embodied carbon!

- We now have the technology to measure, evaluate, and effectively use low-carbon materials to build high-performance houses. Many of these materials are some of the oldest materials we've built with — wood, clay, stone, straw. We now have the experience, scientific understanding, testing and evaluation technology, and modeling software and datasets to put these materials into a modern context.
- Rather than a future vision, the low-carbon high-performance home is both a practical reality and an urgent need. When setting your values, goals, and strategies, we encourage you to hold climate action as a value, zero-carbon building as a goal, and using low-carbon materials as a strategy!

Socio-ecological Equity

This term may not be familiar to everyone. In recognizing that what is good for the planet is generally also good for people, and that negative environmental impacts directly relate to negative social impacts often borne by the most vulnerable of members of our population, we must consider both the social and ecological impacts of our buildings as one and the same. This issue is important to address, for several reasons: 1) these are often "invisible" issues, as the damage may be inflicted many miles away from the building site, either prior to or after the building's useful service life; 2) there is not always a built-in financial or other direct incentive experienced by the stakeholders prompting them to make decisions in support of socio-ecological responsibility, so a strong intention to keep these priorities visible is required; and, 3) in many cases — especially regarding global climate change — there is the need for immediate action to avoid catastrophic results such as species extinction, flooding and droughts, or irreversible climate destabilization. Every building can potentially either exacerbate these problems or provide solutions. If we truly take seriously the perspective of building science in the development of our buildings, we must consider a broader context of applied science that not only evaluates how heat and moisture work upon our buildings, but how the development of our buildings work upon our social and ecological support systems.

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Table 1.5

Value: Socio-ecological Equity	
Goal: Reduce atmospheric carbon loading	
Strategies	***Actions***
Same as for Resource Efficiency	Same as for Resource Efficiency
Reduce embodied carbon of building	Choose low-carbon building materials and practices.
Goal: Reduce fossil-fuel consumption	
Same as for Resource Efficiency	Same as for Resource Efficiency
Goal: Reduce toxic footprint	
Same as for Resource Efficiency	Same as for material Resource Efficiency.
Use non-embodied-toxic materials	Select materials that have a reduced industrial toxic footprint, avoiding petrochemicals, intensively mined and processed materials, and chemical solvents.

Resiliency

As we continue to move through the 21st century, we find an increasing value placed on buildings that can respond to both incidental disruptions caused by specific events (i.e., storms, droughts), as well as long-term disruptions caused by a changing energy landscape, climate patterns, and resulting social and political impacts. To that end, there has been much discussion in the green building world about *resilient design,* focusing on buildings that can adapt to the known and unknown changes and stresses of the century ahead — and thrive.

Fig. 1.4: *For homes run on critical electric systems, a stand-by generator may be relevant, particularly in rural locations or areas where grid power is less reliable.* Credit: New Frameworks Natural Design/Build.

Making a Plan

Clearly, many strategies will support multiple goals and values — a great example is the strategy of building a high-performance enclosure. Accordingly, we devote the majority of the rest of this book in service to this approach. Having identified this, however, the design details of this enclosure, as balanced against cost, time frame, and other practical logistics, will vary greatly based on your own hierarchy of values and the goals you choose to set. So, take some time to get clear on what it is you want, and let us now begin to explore the strategies available to us.

Table 1.6

Value: Resiliency	
Goal: Simple, reliable, adaptable systems	
Strategies	***Actions***
Provide appropriate HVAC systems	Ensure efficient systems are easy to repair, not reliant on specialized labor, tools, or parts.
Design for adaptability	Allow for the ability to modify mechanical, electric, plumbing, and other services, as well as efficient remodels without compromising integrity of the enclosure.
Goal: Building functionality with service loss	
High-performance enclosure to provide stable interior climate	Follow thermal control strategies of a well-detailed air-tight and well-insulated enclosure, to ensure safe living conditions in the event of power or fuel disruption and resulting HVAC system downtime.
Backup systems for critical functions	Employ backup systems and power supplies to allow critical buildings functions (i.e., HVAC, water supply, refrigeration, communications) to continue by availability of multiple energy sources.
Goal: Community support	
Community integration	Integrate associated food, transportation, energy, and social systems with local and regional communities to support both the operation and function of the building, as well as the social and service needs of the owners. Examples include neighborhood tool sharing, community gardens, and community disaster-response action plans.