Introduction

The primary task of any good teaching
is not to answer your questions,
but to question your answers.
— Adyashanti, *The Way of Liberation*

IMAGINE:

You walk into a brand new building and immediately sense something is different. The structure is all exposed wood — columns, beams, even floor and roof are all great curving slabs of timber elegantly joined together from smaller pieces. The skin and insulation, which you can also see, are straw bound into shapes that shed rain and insulate walls. The foundation is soil from the site transformed by invisible microbes into strong concrete to hold everything up, and the warm, leatherlike floors need no additional covering. It somehow looks like a barn but smells like a forest, and feels more like an inviting bedroom or an elegant museum. It's nicer than any building you've ever been in before.

And it's not a handmade house in the woods — it's a new downtown office building, nine stories high, full of people and filling half a city block. It gathers all the power and water it needs, is elegantly lit by daylight, and processes all of its own water and wastes into soil for the courtyard gardens. And, though you can't see this, compared to what might have been built a decade earlier, its construction put thousands of tons less carbon into the air — and pulled hundreds more tons *out* of the air to serve as its walls, floors, and roof.

The New Carbon Architecture: a building made of sky. For the first time in history, we can and should build pretty much anything out of carbon that we coaxed from the air. We can structure any architectural style with wood, we can insulate with straw and mushrooms, we can make concrete — better concrete — with clay, microbes, smoke, and a careful look in the rearview mirror and the microscope. All of these emerging technologies and more arrive in tandem with the growing understanding that the so-called *embodied carbon* of building materials matters a great deal more than anyone thought in the fight to halt and reverse climate change. The built environment can switch from being a problem to a solution. And it doesn't matter whether or not you accept that climate change is anthropogenic: all the technologies described in the pages to follow make sense for a host of reasons, not least that they are much nicer buildings to occupy, and just happen to pull carbon out of the air.

But to back up a bit . . .

Human beings started building about eight thousand years ago with the dawn of the agricultural revolution, and that extended worldwide moment was arguably the most disruptive in history for us and the rest of life on Earth. Rather than hunt and forage about the landscape for our food, we grew it in one spot, and next thing you know, there was architecture, political states, wealth and poverty, Gutenberg and Einstein, global tension, Lady Gaga, and drive-thru WiFi-enabled hamburger stands in Cairo.

And billions more of us.

We've been developing the art and science of building for these thousands of years, mostly learning from trial and error, but as of the last few centuries also learning and developing via science. We know an awful lot more about how things work than we ever did, but can also dimly see how much we still don't know, such as what most of the universe is made of.

Speaking of what things are made of, in many ways the history of architecture follows the development of materials — the history of people messing around with things they found in the landscape to get bricks, then boards, then toilets, then building-integrated photovoltaic panels. People learned to fire clay to make pottery and bricks, and when the kilns were made of limestone, they discovered that the intense heat also changed the rocks: lime plaster, concrete, Pantheon. In some places the potters saw shiny metal come oozing out of certain heated rocks: copper, bronze, iron, Golden Gate Bridge. Two hundred years ago, the predecessors of modern structural engineers in England placed iron bars in newly invented Portland cement concrete, and architects went wild like they never could before: the Sydney Opera House and every downtown skyline in the world with lights, plumbing, and comfort hundreds of feet in the air. In some places people saw oil oozing out of the ground, then drying to tar: vinyl siding and the interstate highway system, not to mention plywood and air conditioning. And so on. Seems like the party would never stop, but of late the many large and hidden costs have come due, and we have to change not just the way we build, but what we build *with*.

Every modern industrial society has codified systems and materials of construction that are based on abundant fossil fuels, and on having an "away" where we can throw things. All the laws, standards, and codes are still rigidly based on doing things that way, even penalizing and inhibiting those who seek better ways to build. For the past century, it has been increasingly easy and cheap to extract, process, assemble, and transport everything we use in construction, but that won't last much longer. At this writing, in early 2017, fossil fuels are surprisingly cheap due to a variety of global conditions (*Peak oil? Are you kidding?*), so to warn of their limited supply seems ludicrous. But the climate is definitely changing, and the effects are arriving harder and faster than we expected even ten years ago. The "heat, beat & treat" approach to making and processing materials is killing us, as is the notion that we can throw anything we want into landfills, water, soil, or air, because building materials account for about 10 percent of global carbon emissions and 25–40 percent of solid wastes. That just has to change. We have a new ball game.

Some of us who design and build have lately started noticing that Nature builds all sorts of things, and has been doing so for the four billion years of life on Earth. She has a hell of a head start on the trial-and-error path; maybe we can and should peek over her shoulder and see if we can't cheat a bit. How does a mussel build its shell? How do spiders spin their webs? How does a redwood tree stand and remain very much alive at 380 feet — and why doesn't it grow higher? How do birds stay warm and dry at night?

When facing design challenges from the small (How can I illuminate a surface or keep out rain?) to the large (Can nine billion human beings live on Earth without wrecking everything for themselves and the other critters, maybe even be a welcome presence?), we might ask: *What would Nature do?*

Some simple and semi-obvious things come right to mind: Nature runs on solar and geothermal energy with no other external energy inputs, and Nature uses what is at hand either by growing it like a clam grows its shell, or harvesting nearby resources as birds do for their nests. There's no FedEx, there's no power grid, there are no artificial chemicals to worry about.

But you and I live in a highly interdependent industrial society, where the sudden disappearance of FedEx, the power grid, a huge multitude of problematic chemicals, and all the other trappings large and small of modern life, would make for a whole lot of suffering for a whole lot of people. We've built a better life for more and more of us, but at the same time made quite a mess, so can we clean it up? Can we wean ourselves off of the fossil fuel habit? This ship doesn't turn very fast, but can we plot a course to a world that works for everybody?

Sure. Technologically, we're scarily clever creatures. It took less than two and a half years between Franklin Roosevelt authorizing the Manhattan Project and the first atomic explosion in the New Mexico desert (for better or worse). It took only eight years between John Kennedy's proclamation and Neil Armstrong's foot stepping onto the Moon's surface. And both of those projects were designed and executed by men and women using slide rules, unreliable wire telephony, and computers far less powerful than the average laptop of today. When we collectively set ourselves to do something, for better or worse, we tend to get it done. Of late there's been plenty of the better but also far too much of the worse. How about let's change that, and get more better and less worse.

This book offers a few suggestions for a more-better built environment, not so much a road map as a collection of useful essays sketching a new palette of materials for a new century. "Net-zero" buildings that use less energy than they generate are a good start, but don't go nearly far enough; here we point out how to design and build truly zero carbon buildings: the New Carbon Architecture.

10%

How much impact might this make on climate change? That would be a rich and nuanced topic for a graduate level thesis, and we hope someone takes up the challenge. But the short answer is: a lot. According to the United Nations Environment Programme, "Though figures vary from building to building, studies suggest that . . . generally 10 to 20 percent of [global] energy is consumed in materials manufacturing and transport, construction, maintenance and demolition."[1]

Various and multiple other studies assign building materials 5 to 15 percent of global emissions, there being no consistent methodology nor data sets to draw from. Call it 10 percent of global emissions, and there's your impact. We propose to reduce that number to zero — and then beyond by a new "carbon positive" architecture that builds with the carbon enticed from sky. We are in technological reach, within a generation, of a global construction industry that is not only "Net-zero," generating more energy than it needs to operate, but in its materials pulls more carbon out of the air than it puts up. We can reverse the emissions engine.

I suppose it bears noting that we the authors are unabashed materials geeks (among other talents), but we're not dense. We recognize that the materials of architecture are not the only component of climate-friendly design, much less of climate work writ large. But we do want to make clear that carbon sequestering architecture is an essential component among the many emerging technologies and strategies for climate *cooling*, from energy to transportation to waste management to water. In particular, we have a keen eye on agronomy and the study of soils, and all the gazillions of amazing little creatures therein, for it's starting to look like that's where we will find real wealth and the wisdom to grow food, clothing, and shelter in fantastic, lovely, and healthy new ways — not to mention sequester stupendous amounts of carbon. We take pride and delight in joining the broader climate effort, and hope you will find useful the news we bring and the vision we share. It's a whole new and lovely ball game.

A Word about "Carbon"

> *I know you believe you understand what you think I said, but I'm not sure you realize that what you heard is not what I meant.*
>
> — Richard Nixon

Carbon. It's a good thing. Right up there, Number 6 in the periodic table, and one of the most common elements on Earth. Carbon is here because a very, very long time ago uncounted millions of first-generation stars created it by nuclear fusion in their cores, then offered it by supernova explosion to the universe. Along with all sorts of other elemental fusion dust, it floated around, eventually to condense by gravity into planets and the world we know. And, as many have noted, it is the party animal of elements: it loves to bond with things like nitrogen, iron, hydrogen, and oxygen to make all sorts of interesting delights such as giraffes, redwood trees, poodles, and you. You read these words with carbon eyes, and hold this book with carbon hands. Please enjoy; not every blob of stardust gets to be conscious for a brief few moments under the sun and run around on a lovely planet with all sorts of other delightful carbon blobs. Congratulations, you lucky dog!

Carbon is a good thing, but too much of anything in the wrong place becomes pollution, or even poison. This book is but one of thousands of efforts to reverse the increase of gaseous carbon in the air, which is disrupting the climate in ways that we can't fully predict, and so far mostly don't like. So we enthusiastically join the growing conversation for climate solutions, but must first be clear about the terms we use. *Carbon* is bandied around a lot, but people often mean slightly different things by it.

3.67

Carbon and *carbon dioxide* (CO_2), for example, are two different things, though they get interchanged quite a lot in climate conversations. The fraction of carbon in carbon dioxide is the ratio of weights: the atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44 because it includes two oxygen atoms that each weigh 16. You switch from one to the other with this formula: one ton of carbon is equivalent to $^{44}/_{12}$ = 3.67 tons of carbon dioxide. (Methane, or CH_4, a major greenhouse gas with 86 times the warming potential of CO_2, has an atomic weight of 16, so the ratio is less pronounced: a ton of carbon in your building equals $^{16}/_{12}$ = 1.33 tons of methane in the air.) Plants like straw (about 35–50 percent carbon) or softwoods (about 50 percent carbon) *sequester* (that is, durably store) carbon by absorbing carbon dioxide and releasing the oxygen. They feed us oxygen with their respiration, and we oxygen-breathing creatures feed them CO_2 with our respiration. Cool deal, huh? A ton of carbon in the forest or field — or as part of a building — represents or simply is 3.67 tons of carbon dioxide absorbed from the air.

Also, following convention, we will sometimes use *CO_2e* to denote carbon-*equivalent* emissions from carbon and other gases such as methane, calibrated according to each one's *global warming potential* (GWP) because some gases have ten or a hundred or even thousands of times the heat-trapping effect of carbon dioxide. Chapters One and Two will define and expand on what we mean by *embodied carbon* aka *carbon footprint*, but from here on out, we'll use those terms to connote embodied carbon equivalents, or eCO_2e. We might also sometimes be lazy and just say "carbon" when we mean CO_2e emissions, but we trust you'll get the drift without confusion.

Finally: *embodied energy* and *embodied carbon*. Be warned that terms like *zero energy* (aka ZE), *net-zero energy* (aka NZE), *zero net energy* (ZNE) are all increasingly tossed about in loosely interchangeable ways in conversation around building energy efficiency. Even more confusing, their close cousins *zero carbon* and *zero net carbon* are also appearing more frequently. This is a rather complex matter in itself, as terms change meaning with scale (product, building, community, nation, or globe?), with grid efficiency (coal, hydro, nuclear, wind? etc.), time frame (daily, annualized, or lifetime?), and other factors. In the pages that follow, some authors will variously use embodied energy and embodied carbon, and for our purposes those are in tandem; that is, though the units for measurement are different, they rise or fall roughly in parallel. (In Chapter Two: Counting Carbon, we discuss how they can diverge, as when products are manufactured with electricity from a coal-dependent grid vs. a hydropowered grid.) The growing consensus is that zero carbon (vs. zero energy) should be our societal goal across all industry, and so we will favor that term from here on out. Even better, we will also sketch out the possibility of a *carbon positive* architecture defined by more carbon sequestered than is ever emitted.

A book made of carbon, written by carbon, for carbon, on how to build carbon shelter to protect us from a sometimes hostile carbon planet.

Shall we dance?

Notes

1. *Buildings and Climate Change*, United Nations Environment Programme, 2009.

Chapter One:

Beyond Zero: The Time Value of Carbon

by Erin McDade

A Global Carbon Limit

In December of 2015, the world came together in Paris for the United Nations' 21st Conference of the Parties (COP21), and signed the historic Paris Climate Agreement. This agreement commits almost 200 countries to helping limit global temperature increase to "well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C."

These temperature increase limits are in response to the international scientific community's widely accepted two-degree Celsius tipping point. Global temperatures have been increasing steadily since the industrial revolution, but the scientific community believes that if we can peak our global increase and begin to cool the planet before we gain two degrees, the effects of climate change will be reversible. In other words, if we meet this target we can return the planet to pre-industrial conditions. However, scientists believe that if we pass that two-degree threshold, the effects of climate change will begin to cascade, spin out of control, and become irreversible.

Buildings Are the Problem; Buildings Are the Solution

In addition to the historic signing, COP21 made history by hosting its first ever Buildings Day in recognition of the crucial role that the building sector must play in reducing global CO_2e emissions. The US Energy Information Administration (EIA) estimates that constructing and operating buildings accounts for nearly half of all US energy consumption and fossil fuel emissions. Globally, cities consume nearly 75 percent of the world's energy, mostly to build and operate buildings, and cities are responsible for a similar percentage of global emissions. The building sector is a significant part of the climate change problem, but this also means that if we can eliminate carbon emissions from the built environment, we can significantly reduce overall emissions, ameliorating and potentially even solving the climate change crisis.

Zero by 2050

According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), the organization that hosts the annual Conference of the Parties, global temperatures have already increased by 0.85 degrees Celsius since pre-industrial times, meaning that we're nearly halfway to our maximum temperature increase threshold. In order to predict future temperature increases as they relate to fossil fuel emissions, the IPCC periodically publishes projections based on a number of global patterns, ranging from business as usual to aggressive emissions reductions. In 2013, prior to the Paris Climate Agreement, the IPCC published four projection scenarios. The business-as-usual scenario, in which our consumption of fossil fuels continues to grow exponentially, projected that we would pass the two-degree tipping point around 2040. Even the more aggressive reduction scenarios, in which global emissions peak between 2050 and 2080 and then begin to diminish, showed us passing a two-degree increase near 2050. While an extra decade below two degrees would certainly be an improvement, following these projections would simply be delaying the inevitable — climate change would still spin out of control and become irreversible. The fourth and most aggressive scenario published, in which global emissions peak and begin diminishing in 2020, gave us our best chance of staying below the two-degree Celsius threshold, but unfortunately still predicted a large chance of surpassing that tipping point.

In response to the Paris Climate Agreement's aggressive target of a 1.5-degree

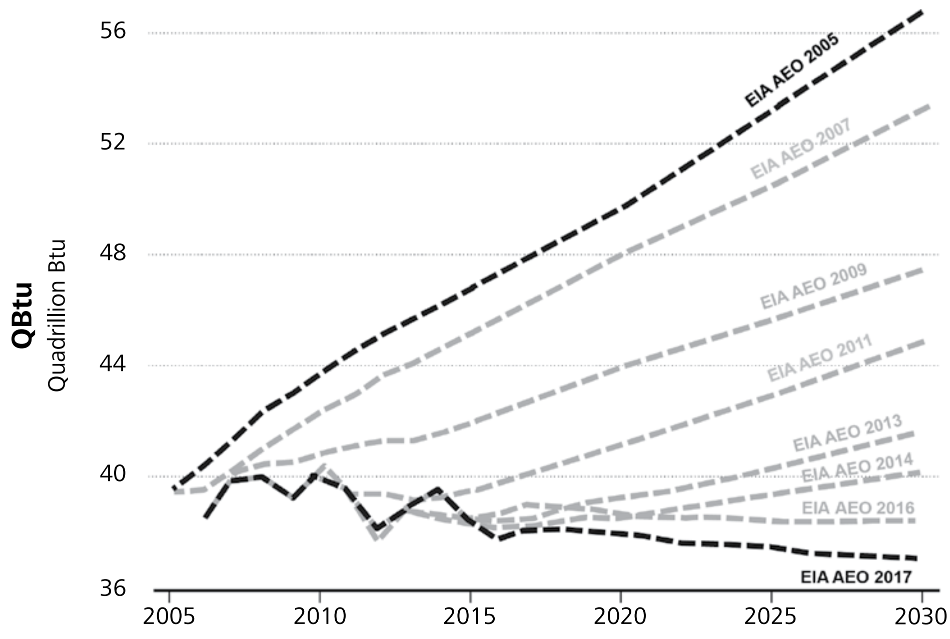

Fig 1.1. **US building operations energy consumption 2005–2030**

Data source: US Energy information Administration, Annual Energy Outlook (EIA AEO)
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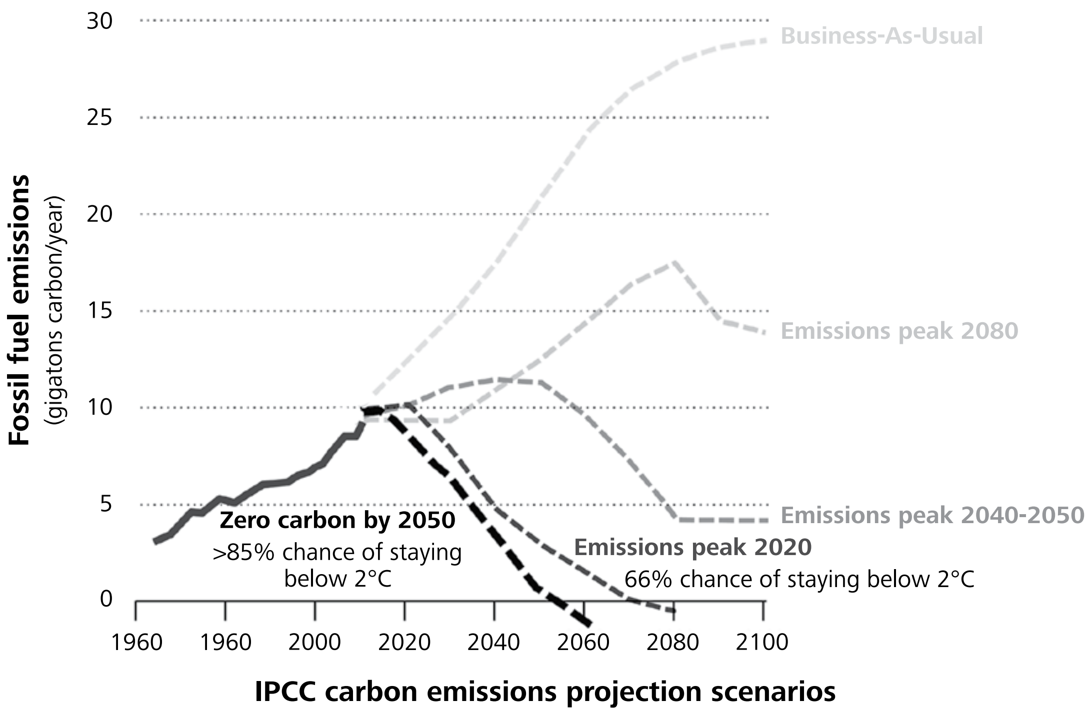
maximum increase, the IPCC published an additional emissions scenario that gives us an 85 percent chance of staying below a two-degree increase. However, this scenario requires global carbon emissions to peak immediately, and for us to fully phase out our use of fossil fuels, in every sector, by mid-century. This means that in order to meet the targets set forth by the Paris Climate Agreement, the global building sector must be carbon free by the year 2050.

The Zero Net Carbon Gold Standard

Since the beginning of the green building movement in the 1970s, the design community has focused mainly on increasing the efficiency of *operating* our buildings — reducing the energy consumed (and carbon emitted) in keeping everyone warm (or cool), keeping the lights on, etc. Both technology and design have improved drastically in the last 50 years, and now Zero Net Carbon (ZNC) is the gold standard for sustainable construction. A ZNC building is a highly efficient structure that produces renewable energy onsite (typically using photovoltaics), or procures as much carbon-free energy as it needs to operate. ZNC buildings are being constructed globally in almost all climate zones, space types, and sizes, proving the viability of this standard, and their reduced carbon emissions are being documented.

Each year the US Energy Information Administration publishes the Annual Energy



Source: IPCC 2013, Representative Concentration Pathways (RCP); Stockholm Environment Institute (SEI), 2013, Climate Analytics and ECOFYS, 2014. Note: Emissions peaks are for fossil fuel CO_2-only emissions.
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Fig 1.2.

Outlook, predicting future US energy demand based on current consumption trends. In 2005, before Architecture 2030 launched the 2030 Challenge and catalyzed the US and global building communities to begin targeting zero operational emissions by 2030, the EIA's projections predicted exponential growth in building operational energy consumption. Following the launch of the 2030 Challenge, each subsequent year's projections showed a decrease in energy consumption, and projections flatlined in 2016. The EIA's 2017 projections predict that US building operations will consume less energy in 2030 than in 2005, despite consistent and significant growth in the building sector. With this downward trend, and the increasingly frequent construction of ZNC buildings, the world seems on track for meeting the widely adopted commitment to zero operational carbon emissions by the year 2030.

Embodied Carbon: Getting to Real Zero

However, the emissions resulting from operating our buildings only represent one side of the coin. In fact, even before a building is occupied and any energy has been used for operation, the building has already contributed to climate change — usually in a significant way. These mostly unnoticed effects are the result of the construction process itself, and include emissions resulting from manufacturing building products and materials, transporting them to project sites, and construction. We refer to this as *embodied energy* (energy consumed pre-building operation) or *embodied carbon* (carbon emitted pre-building operation). To date, even within the green building community, these emissions are usually ignored in the conversation about the building sector and climate disruption.

On day one of a building's life, one hundred percent of its energy/carbon profile is made up of embodied energy/carbon. Embodied carbon emissions end upon the completion of construction, while operational carbon is emitted every day for a building's entire life. (Well, not quite. All buildings get maintained, painted, reroofed, remodeled, added to, repaired, and so on, causing embodied carbon to continue to climb slightly in short bursts. But for most buildings this effect is minor by comparison, so for this discussion we treat embodied carbon as just that from the original construction.) Over the life span of a typical building, the cumulative operational emissions almost always eclipse the initial embodied ones, and by the end of the building's life, embodied energy accounts for only a fifth or less of the total consumed by the building. Even if that same building is constructed to operate twice as efficiently, cumulative operational emissions are still greater than initial embodied ones. (See Figure 1.3.)

Since embodied energy accounts for an average of 20 percent of a building's total energy consumption over its life, it is understandable that the building sector's historic focus has been on operational (instead of embodied) energy and carbon. However, with the signing of the Paris Climate Agreement committing the world to a carbon-free built environment by 2050, we clearly can no longer ignore embodied carbon. In fact, new research indicates that to date we have significantly underestimated the significance and time sensitivity of embodied carbon in overall building sector emissions.

Emissions Now Hurt More than Emissions Later: The Relative Importance of Embodied Carbon

Over a typical building's 80–100-year life span, operational emissions dwarf embodied emissions. But if our deadline for eliminating building sector emissions is three decades or less, the timeline is much shorter and the relative importance of embodied carbon changes. Assuming a building is constructed today and operates 50 percent more efficiently than a typical building, by 2050 only 45 percent of the energy consumed by that building will have been used for operations, meaning that 55 percent of that building's total energy consumption is embodied energy. And the closer to 2050 the building is constructed, the more embodied carbon emissions eclipse operational carbon emissions. Furthermore, as we target ZNC for all new construction and buildings are designed to meet increasingly rigorous performance standards, the amount of operational carbon emitted decreases and is eliminated, meaning all of a building's carbon emissions are the result of embodied carbon. (See Figures 1.4 and 1.5.)

Embodied Carbon in the Future

Between 2015 and 2050, more than two trillion square feet of new construction and major renovations will take place worldwide,[1] the equivalent of building an entire New York City (all five boroughs) every 35 days, for 35 years straight! If the built environment is to be carbon free by 2050 and meet Paris Climate Agreement targets, how we in the design community design and construct this two trillion square feet, and how we value and evaluate its embodied carbon, is crucial.

Even conservatively assuming that all of this new construction operates twice as efficiently as typical construction, between now and 2050, 80–90 percent of its energy profile will be made up of embodied, not operational, energy. The carbon math is similar though not identical due to variations in grid energy emissions.

This isn't to say that operational performance isn't important. Barring major renovations, a building's operational emissions patterns are locked in on day one: an inefficient building constructed today will probably still be inefficient in 2050. And while major renovations, in which we upgrade to Zero Net Carbon standards, are an important part of decarbonizing the built environment, each renovation requires new building materials and more construction, which further increase emissions. (See also Chapter Three: Rebuild, by Larry Strain.) It is crucial that we consider immediate embodied carbon impacts when constructing this massive additional building stock. Sometimes, that may even mean valuing lower embodied carbon strategies, or better, using carbon-sequestering materials as presented in the rest of this book, over carbon-intensive strategies that only minimally improve operational performance.

The Time Value of Carbon

Without a deadline, we might continue to dismiss embodied carbon impacts as minimal compared to operational carbon. But climate change is urgent: all carbon emissions must be eliminated from the built environment by the year 2050. In traditional analyses of embodied vs. operational carbon, which consider the building's whole life span, rarely are initial embodied carbon outputs as impactful as the operational savings that they allow — high-performance design savings almost always pencil out as worth the embodied carbon investment. But as high-performance construction becomes the standard, and designers increasingly work to eke out every last drop of operational savings, that little bit of improved performance often won't balance out the required embodied carbon investment for decades — well past our 2050 deadline. Therefore, any carbon reduction strategy we consider must be evaluated based not only on potential savings, but also on how quickly those savings can be achieved. If, for example, adding fixed shading to a new building will improve its performance so much that the increased operational savings exceed the added materials emissions in at most a few years, that may be a smart strategy. But if adding an extra inch or two of carbon-intensive, high-density insulation improves efficiency by a few percentage points, but it takes 50+ years for the operational improvements to outweigh the embodied costs, is that the right choice? (Hint: No.)

To have any hope of meeting our climate change goals, we must rethink our traditional carbon analysis mechanisms and design processes. Whole building life spans do not accommodate the urgency of climate change; carbon emitted today has much, much more impact than carbon emitted after 2050, and we can't continue to underestimate the effects

Who cares about embodied carbon?

Operational emissions are far bigger, right?

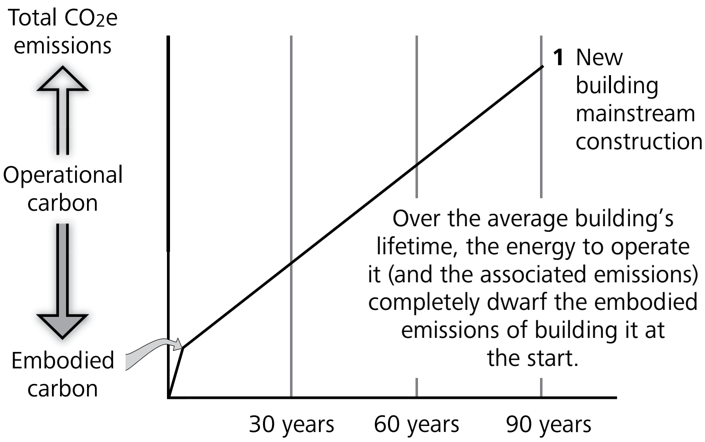

Fig 1.3: *For the first decades of green building, no one thought that embodied carbon mattered very much.*

Moving from mainstream *to* efficient *to* net-zero

BIG improvements!!!

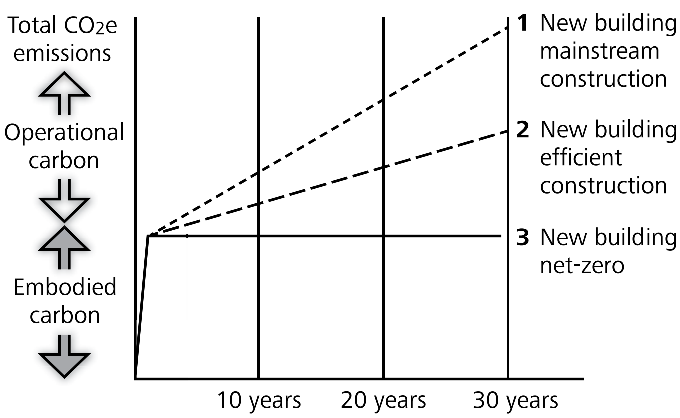

Fig 1.4: *Most of "green design" to date is about reducing operating energy (or carbon emissions).*

of embodied carbon emissions. If our remarkable success in high performance design continues, embodied carbon may well prove to be our downfall — or the key to solving climate change. It's up to us to decide.

The effect on the climate is = time x emissions

The *impact* is the grey area under the curve

Emissions are hugely amplified by ***when*** they occur — embodied carbon is greatly weighted, very much like the time value of money.

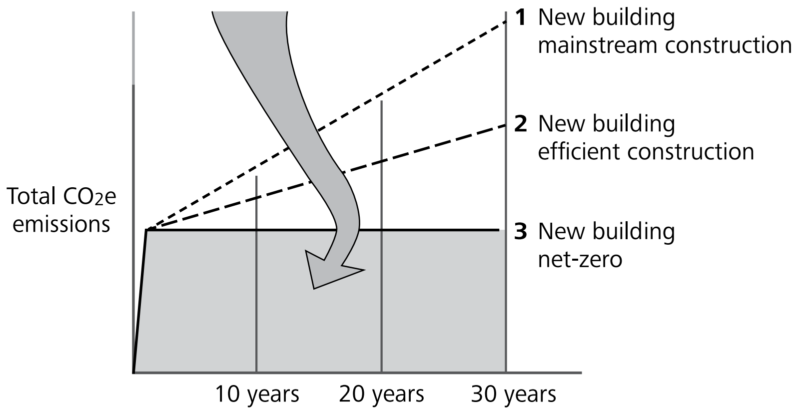

Fig 1.5: *But, oops! We're suddenly realizing that embodied carbon matters a lot, and is about half to three-fourths of the climate impact of your next project over the next two decades.*

1, 2, and 3 all have *big climate impacts* because they emit carbon right from the start

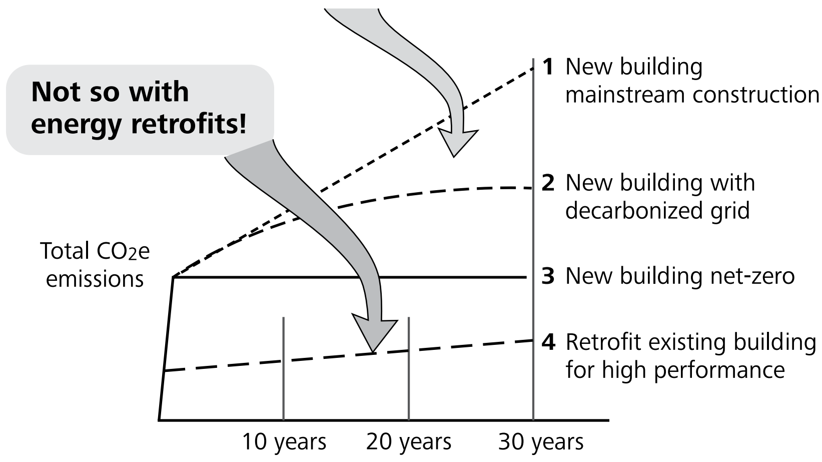

Fig 1.6: *The good news is, we can have both: low to zero operating and embodied emissions.*

Zero Energy in a Nutshell

by Ann Edminster

The US Department of Energy defines a zero energy building as "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy."[2] Notably, embodied energy is not included in this widely used definition; nor is transportation energy, nor are other components of personal energy use. Nonetheless, leaders in the green building community have been concerned with these other components for a long time.[3]

Zero energy (aka ZE, net-zero energy, NZE, zero net energy, ZNE) building as a concept has been in play in the energy efficiency community for approaching two decades, with attention increasing following Governor Arnold Schwarzenegger's 2005 executive order decreeing that by 2020, all new California homes would be zero energy, and by 2030, all the State's new non-residential buildings would follow suit. As 2020 has gotten closer, the rate of activity in the ZE arena has been accelerating. Today, ZE built projects and policy initiatives exist all around the globe, with California still at the forefront of ZE in North America, closely followed by the US Northeast.[4]

Passive House (Passivhaus), another burgeoning energy efficiency movement, is rapidly converging with ZE, as building professionals increasingly adopt the Passive House framework to facilitate attaining the high level of efficiency needed to achieve ZE.

Zero energy leaders have long acknowledged that ZE at the community scale is their real target, with focus shifting more recently to zero *carbon* communities. This has a number of far-reaching and challenging technical and policy implications related to electrification (elimination of natural gas, fuel oil, and propane in building operations), transformation of the utility grid, and aggregating energy demand and renewable energy production of individual buildings in order to achieve zero carbon operations at community scale.

At the same time, there is still much to be learned about achieving zero energy at the building scale, including factoring in embodied energy/carbon. By and large, the energy efficiency community still believes that embodied energy is of less concern than operating energy, because it is a smaller portion of the energy pie. However, the authors of this book, among others, have come to realize that with the element of time of utmost importance in the climate change equation, more attention to embodied energy/carbon from the ZE community is overdue. Some groundbreaking projects are beginning to tackle this challenge, notable among them the redesign of Terminal 1 at San Francisco International Airport, where the design team is analyzing embodied carbon of various design alternatives alongside operating energy, to enable them to make informed decisions about the overall energy/carbon performance of the design options.

Notes

1. IEA. 2016. Energy Technology Perspectives 2016, IEA/OECD, Paris.
2. DOE has formulated companion definitions for ZE campuses, portfolios, and communities.
3. As one such example, Dr. Raymond Cole, University of British Columbia, in the mid-2000s proposed a schema for personal energy uses that comprised household operating energy, routine personal transportation energy, the energy embodied in durable goods, in the food we eat, and in our vacation activities.
4. Net-zero Energy Coalition. 2016. *To Zero and Beyond: Zero Energy Residential Buildings Study*.