

Sustainable and Energy-Efficient Development Interventions and their Application toward Net-Zero or Net-Positive Energy and Water Building Development

by

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Submitted to the Program in Real Estate Development in Conjunction with the Center for Real Estate in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development

at the

Massachusetts Institute of Technology

September, 2016

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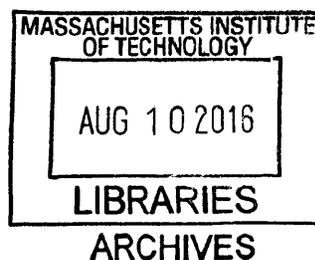
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ABSTRACT

The built environment consumes more than 40% of the energy used around the world and nearly 70% of the electricity used in the United States. These same buildings use 25% of the world's fresh water resources and contribute 50% of global waste. In order to make the buildings we inhabit more resource-efficient, strategies are being employed through the use of technology, materials, and design in order to achieve a new standard of environmental impact, called net-zero buildings. To date, only a few dozen buildings in the United States have achieved net-zero or net-positive energy and water status, where they capture as much or more energy and water through renewable energy resources and water collection and reuse mechanisms as they use on an annual basis.

This thesis examines the many energy- and water-efficient systems, design solutions, and materials that work together to create more sustainable structures and presents case studies for two highly-efficient developments. These net-zero interventions are then compared to the highest-scoring Leadership in Energy and Environmental Design (LEED) buildings across the United States in an attempt to detail the similarities and differences in the goals of each system. Research of the top 10 highest-rated investor-owned buildings shows a significant gap in performance between the systems and design elements used to achieve LEED Platinum status and the energy and water interventions that are necessary to reach net-zero consumption goals.

The gap in performance between LEED and net-zero design is related to regulatory hurdles, technological advancements, and the sophistication of design teams. Combined, these influence the commercial diffusion of net-zero development projects and can be used to understand how the built environment can start to meet sustainability goals.

Thesis Supervisor: Dr. Andrea M. Chegut
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Acknowledgements:

I'd like to first thank my parents, Bryan and Laura, who always pushed me to work hard and give nothing but 100% in everything. I would not have made it this far if it were not for you both.

Second, to my sisters, who were always smarter than I was. For always giving me something to strive for, always reminded me that I could know more and could be better. Thanks for the challenge.

To Heather, who showed me how to take leaps and not fear the unknown. The first always forges the way and you did a great job. From college across the country, to working across an ocean, to tackling the capital of the world. Thanks for teaching me to never be afraid of big things.

And to Caitlin, the brilliant engineer who showed me what it was like to work hard and cultivate a successful career. And for letting me live on your couch that one summer. Thank you.

To the HHI group chat, Carl, Drew, Matt, Dave, Doug, Chris, Blair, Johnny and Josh, for getting me through this year with memes, political insights, sports talk, and anything else to keep me from taking myself too seriously. You guys were always a welcome respite from the grind.

To Laura, who has listened to me on good days and bad, who has been there through it all over the last year, and who has been selfless enough to engage in endless real estate talk. I will always be in awe of what you do and how well you do it.

To the faMITY, what started as a Geltner homework group really did become a family. I can't thank you guys enough for being a great group of friends to lean on over the last year. The Avi Factor is real.

To the entire MSRED class of 2016, the Cap Rate Kids. We really did have an amazing group of people come together for an extraordinary year. I look forward to working with many of you down the road.

To the faculty and staff. Thank you for guiding us through one hell of a year. And to Tricia and Bridget, for making sure we all made it out alive.

To the team at CBRE. Simon, Biria, Jim, John and Aliza. The time spent there prepared me for all the hard work that came at MIT. Our team became my first family in Boston and I will be forever grateful for all that you taught me.

To Simon Butler, Biria St. John, Andy Hoar, and Yasmin Kor, who wrote letters of recommendation.

To Tod McGrath, Peter Merrigan, Vin Norton, Canan Safar, and Michael Tilford. For taking the time to talk about the program and putting me on the right track toward what has been a great year.

And to Dr. Andrea M. Chegut. For continuing to push me to a meaningful conclusion throughout this thesis process. It was a great learning experience.

QED.

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Introduction

As populations expand and resources become scarcer, humanity will need to move toward a less impactful existence by changing the areas of our lives that are unsustainable. One of the biggest contributors to resource consumption across the globe is the built environment. According to the United Nations Environment Programme (UNEP), buildings use about 40% of global energy, 25% of global water resources, and create 50% of global waste. Furthermore, residential and commercial buildings consume approximately 60% of the world's electricity,¹ and as the rest of the world continues to move toward more developed economies, that number is expected to increase.²

According to the U.S. Energy Information Administration (EIA), 87% of U.S. electricity generation in 2015 came from non-renewable energy sources that emit harmful chemicals and pollutants into the atmosphere and exacerbate the current environmental crisis of habitat deterioration and global warming.³ In order to change the current energy situation, a new normal needs to be adopted within the real estate industry. Given the scale of energy consumption stemming from the built environment, what are the interventions that can be made to systematically decrease energy consumption and drive the building stock to a net-zero or net-positive energy and water solution?

Sustainability can be achieved through increased efficiency in the use of buildings and technological advancement in the design, systems, and materials used. Today, the built environment has already made large strides toward sustainability. LEED-certified buildings have been proven to use 25% less energy than their competitors, all else being equal.⁴ In 2012, the Bullitt Center in Seattle became the first office building in history to achieve the Living Building Challenge certification and the largest multi-story office building to achieve net-zero status. In fact, in its first year of operation, the building was actually net-positive in its energy use.⁵ This building signifies the frontier of what is possible within the built environment, and will be discussed in greater detail in the second section of this thesis.

Given the current state of technology and design solutions, all new buildings have the real option to use available design elements to be as energy-efficient as possible. Within the engineering and design sectors this is referred to as net-zero ready. Regardless of where the energy is supplied, the building uses as little of it as possible. Once at net-zero *ready* status, a building can utilize renewable energy sources to capture as much energy as it uses, allowing the project to achieve full net-zero status.

¹ <http://www.unep.org/sbci/AboutSBCI/Background.asp>, July 6, 2016.

² <http://www.eia.gov/todayinenergy/detail.cfm?id=12251>, July 27, 2016.

³ http://www.eia.gov/energy_in_brief/article/renewable_electricity.cfm, July 5, 2016.

⁴ <http://www.usgbc.org/articles/business-case-green-building>, July 20, 2016.

⁵ <https://newbuildings.org/wp-content/uploads/2015/11/2015ZNEbuildingsList1.pdf>, July 19, 2016.

According to expert sources, there is enough potential energy from renewable sources to cover all global energy needs thousands of times over; in the deserts of the Southwest U.S. there is adequate solar power to fuel the entire country,⁶ and scientists at the Institute of Solar Research estimate that in the deserts of the Middle East and Northern Africa (MENA), there is enough energy to provide 40 times the electrical demand of the entire world on an annual basis.⁷ Through continuous innovative pursuits we can convert that potential energy into the fuel that will power our world in the coming centuries.

Because each piece of real estate is unique, there is no one solution to this complex problem. What works in the windswept, sun-soaked, dry deserts of Northern Africa will be different than the successful solutions seen in a more-often-than-not cloud-covered Seattle, Washington. It is an integrated design approach that brings many of these interventions together in the right combination to create a better building. In the following pages, this thesis will assess the interventions and ideas that are available to designers, buildings, and tenants that can be combined to create net-zero projects.

Currently, there are only a few places that have tried to catalogue these interventions, and they are generally described at highly technical levels. The U.S. Green Building Council,⁸ Environmental Protection Agency,⁹ U.S. Department of Energy,¹⁰ various private environmental organizations, and manufacturers of these technologies have put together catalogues to describe some of the building features and technological solutions. However, many of these focus on specific brands, or only focus on energy, water, design, or waste treatment, and are not comprehensive across all possible systems.

This thesis strives to provide a comprehensive overview of every type of intervention and to introduce strategies through the integration of design and technology that can make a significant impact on the energy consumption of the built environment. It will also enable a central location for a comprehensive suite of sustainable solutions to date. If homeowners, renters, office workers, building laborers, financiers, private equity firms, REIT shareholders, developers, construction firms, architects, engineers, and building management personnel are more aware of these interventions, a broader and better-informed discussion can take place around the changes that are necessary to achieve more sustainable and energy-efficient buildings. These are places where we live, work, learn, and relax on a daily basis, and we all need to be involved in making them assets, not just financially, but in terms of the urban ecology of our cities.

In this way, this thesis identifies the many energy- and water-saving solutions that exist in today's built environment, some of which have been quickly and universally adopted and some of which continue to be ignored, despite their potential for success. This thesis examines the evidence from the most

⁶ Maclay, 8.

⁷ Knies, 1.

⁸ <http://www.usgbc.org/education-at-usgbc>, July 18, 2016.

⁹ <https://www.epa.gov/energy>, July 18, 2016.

¹⁰ <http://energy.gov/science-innovation>, July 18, 2016.

sustainable buildings across the United States in order to identify which strategies, systems, and design elements are being incorporated into these cutting-edge buildings.

In addition, I analyze the top 42 LEED Platinum buildings in the U.S. to derive the prevalence of each building intervention. The contribution is the identification of the technologies that are used in the most sustainable buildings to date. This gives insight into which technologies have become accepted as feasible in the market and which have not. There are many interventions that are in their infancy or have not reached a point of economic feasibility, but that may help us complete the goal of a renewable energy-fueled world in the future. Many of those technologies are promising but may be underutilized until additional advancements make them beneficial to projects, policy hurdles are overcome, or economic incentives are aligned.

In summary, the contribution of this thesis is to identify building design and technology interventions that cultivate a sustainable, energy- and water-efficient built environment. The process toward green development has taken more than 40 years with significant research, development, and expertise, but with the technological advances of the 21st century, hopes are that the adoption of such practices will increase as these advancements become more efficient and commercially viable.

The thesis will proceed as follows: Part I will discuss the history of design interventions, the development of energy-efficient outcomes, and the legislation that has led this country to more sustainable building standards. Part II will identify and briefly explain each of the sustainable interventions that exist within the built environment. Part III will look at two state-of-the-art buildings in a case study format to identify and explain how each building is using design and technology to create better buildings. Next, Part IV will analyze the highest-scoring commercial buildings according to USGBC's LEED designation scoring system and identify how many sustainable design and technology interventions each uses along with the trends seen from the data. Finally, Part V will draw conclusions on the current state of sustainable development and look to the future of the technology, policies, and developers leading us toward a net-zero urban landscape.

Part I: Sustainable Design Interventions, Systems, & Outcomes

This first section outlines the history of sustainability, the wide spectrum of attitudes toward building design, the impetus for research and development of efficient technology, and the political push for sustainability and energy-efficiency within the built environment as energy ceased to be an inexpensive commodity. We look at what caused the introduction of new technologies and how government stepped in to initiate the process of more environmentally-friendly building practices.

Design Interventions

Sustainability is not a new concept and the history of energy-efficient buildings is a long one. Even ancient humans understood the power of sunlight and designed buildings around what we now refer to as passive solar design, orienting buildings to make the most of the day's sunlight. In Chaco Canyon, New Mexico at a place called Pueblo Bonito, there was evidence of this type of design, thought to be built as early as the 9th century.¹¹ Fast forward to the mid-19th century, and we find architects of the Galleria Vittorio Emanuele II in Rome were using methods to decrease impacts of structures on the environment, such as roof ventilators and underground cooling chambers to regulate indoor air temperature.¹² In the United States in the early 20th century, buildings in New York City like the Flatiron Building and the New York Times Building were using windows set back from their concrete façades to reduce sun exposure and heat gain before the days of air conditioning. The concept of passive solutions for energy savings and occupant comfort has been around for centuries. However, as the Industrial Age propelled us to new heights and the discovery of inexpensive fossil fuels made it easier to heat and cool space, civilization no longer had a need for these simple solutions. Technology allowed us to ignore nature's solutions and build a world fueled by an abundant supply of cheap energy.

In the mid-20th century, HVAC systems, reflective glass, and steel structures all became the popular building technique across the United States. These larger buildings were heated and cooled by massive air handling systems that used exorbitant amounts of fuel.

It was only in the 1970's, with higher fuel costs and an oil crisis on hand, when architects, environmentalists, and ecologists began to refocus efforts on energy-efficiency, and so began the modern-day movement of sustainable development. Around this time, the American Institute of Architects formed a Committee on Energy, which focused on both passive design elements and technological solutions. As energy concerns subsided, however, the movement lost steam and only a few buildings and institutions continued to pursue cutting-edge energy efficiency.

¹¹ Maclay, 76.

¹² <http://www.marble-institute.com/default/assets/File/consumers/historystoneingreenbuilding.pdf>, July 7, 2016.

Systems

It was because of this energy crisis that the country realized the need for energy-efficiency on all fronts, not just building technology. Research continued on the subject through the 1970's, 1980's and 1990's, and resulted in more effective technologies, including solar panels, pre-fabricated modular construction of efficient wall systems, water reclamation systems, smart grid technology, daylighting strategies, more fuel-efficient transportation, etc. In 1990, the Building Research Establishment published BREEAM (Building Research Establishment Environmental Assessment Method) for assessing, rating and certifying the sustainability of buildings.¹³ For the first time, industry leaders began to realize how much energy buildings were consuming and began to seek strategies to mitigate the impact.

Later, policy changes were implemented by government agencies that led to the adoption of more efficient building systems. Standards were being created for energy-efficiency that forced manufacturers to seek better alternatives and better technology.¹⁴ There were energy-efficiency provisions in the National Affordable Housing Act of 1990 and the Energy Policy Act of 1992 that pushed these initiatives further. Because of this, suppliers and consumers were forced to adapt. Through the vast amount of research and technology that had been pursued over the previous three decades, systems were developed that continuously improved their efficiency, meeting the standards set by legislation.

Also in the 1990's, the U.S. government propelled the movement forward by applying these new energy-efficient solutions to government buildings like the White House, Pentagon, and the U.S. Department of Energy building.¹⁵ The White House was the first, and used all the latest technology of the time to become as energy-efficient as possible. It made alterations to the building façade to make it tighter and decrease the loss of energy through the roof, windows, and walls. It used the most efficient lighting solutions of the time, utilizing energy-efficient light bulbs and taking advantage of daylight. Energy-saving office equipment and appliances were installed. A comprehensive recycling plan was implemented and vehicles that burned cleaner fuels were leased in favor of older, less efficient models. Energy efficiency was back in the spotlight, and building owners had to get on board or face the consequences.

Outcomes

In 1993, the U.S. Green Building Council (USGBC) was formed and began to put in place a rigorous framework for energy-efficient design and development.¹⁶ It was in 2000 when the Leadership in Energy and Environmental Design (LEED) rating system was introduced publicly. Adoption was slow at

¹³ <http://www.breeam.com/why-breeam>, July 23, 2016.

¹⁴ https://www.ase.org/sites/ase.org/files/resources/Media%20browser/ee_commission_history_report_2-1-13.pdf, July 21, 2016.

¹⁵ <http://www.marble-institute.com/default/assets/File/consumers/historystoneingreenbuilding.pdf>, July 7, 2016.

¹⁶ <http://www.usgbc.org/about>, July 7, 2016.

first because the concept was unproven and therefore required taking on risk, the enemy of any real estate developer. Financial institutions were more comfortable lending on projects that had a proven track record of success rather than new, innovative projects that had higher risks associated with them. However, as cities like Boston, San Francisco, Miami, and Kansas City began to amend building codes to include the USGBC's rating standard of LEED certification, adoption increased.¹⁷

Legislation has continuously been updated to push the standards of energy-efficiency further. The federal Energy Policy Act of 2005 built on the 1992 legislation, and states like California are requiring standards even stricter than many energy-efficiency programs. All this work has led to the use of less energy on a per capita basis than in 1970. Back then, Americans used the energy equivalent of 2,700 gallons of gasoline on an annual basis across all activities. By 2010, even with the increased use of electronics, we had reduced that number to the equivalent of 2,500 gallons.¹⁸

Today LEED design is the standard for new buildings in many cities and states across the country. The building sector has decreased energy consumption by 11% in residential buildings and 21% in commercial buildings since 1980.¹⁹ However, the next step in the evolution of sustainability in the built environment is net-zero development. As with the adoption of any new system, it will take time even though the technological pieces already exist.

Green buildings have proven their worth within the real estate investment world in recent studies, however adoption is still happening at a modest pace. Across five different studies analyzing LEED-certified, BREEAM-certified and ENERGY STAR-rated buildings, there was unanimous evidence of price premia. In 2010, studies by Eichholtz²⁰ and Wiley²¹ found premia for ENERGY STAR-rated and LEED-certified buildings of 16.5% and 13%-55%, respectively. A year later, Fuerst and McAllister found value premia of 30% for LEED-certified and ENERGY STAR-rated buildings, noting that the premium grew with the level of certification.²² In 2013, another study showed an average premium of 13.3% for sales of these green buildings compared to non-certified buildings.²³ And lastly, in 2014, Dr. Andrea Chegut, together with her research partners Piet Eichholtz and Nils Kok, looked at BREEAM-certified buildings and found a 17% price premium.²⁴

However, there are still externalities like the benefits to the environment and to the public that are not priced into these buildings. For instance, the burden removed from a municipality for on-site water

¹⁷ <http://www.everbluetraining.com/blog/cities-requiring-or-supporting-leed-2015-edition>, July 23, 2016.

¹⁸ https://www.ase.org/sites/ase.org/files/resources/Media%20browser/ee_commission_history_report_2-1-13.pdf, July 21, 2016.

¹⁹ National Research Council, "Real Prospects for Energy Efficiency," 4.

²⁰ Eichholtz, et al., 2010.

²¹ Wiley, et al., 2010.

²² Fuerst, et al., 2011a.

²³ Eichholtz, et al., 2013.

²⁴ Chegut, et al., 2014.

capture and storm runoff mitigation is not priced into traditional financial models. All that said, it is surprising given the aforementioned data that developers are not pursuing sustainable buildings 100% of the time, when the evidence for higher values has been proven several times over.

Part II: A Catalogue of Sustainable Interventions

Much of the net-zero research has been spearheaded by the Department of Energy and the National Renewable Energy Laboratory (NREL).²⁵ The current solution as proposed by net-zero development is implemented through a combination of energy, water, waste, design and material choices. The key to successful net-zero development is integrated design, a well-assembled unification of interconnected systems curated to work synergistically. William Maclay, in *The New Net-Zero*, outlines a number of core principles for pursuing net-zero building development. The first and probably most obvious is the conservation of energy and resources.

Second, let nature do the work. The sun, wind, and rain are all resources that we can take advantage of without doing damage. If a developer is able to make the most of these resources on the site, the building will be that much closer to energy and water neutrality. The last core principal he outlines is the design and development of passive systems before active ones. Passive systems are those that require no mechanical power, such as daylighting and natural ventilation. He recommends starting with the most natural and easiest interventions, then building to the more advanced technology to complete the objective.²⁶

Net-zero can refer to a number of things, including energy, water, and carbon emissions and can also vary in its scope, from day-to-day operations all the way to “Cradle-to-Grave”, or planning, development, useful life, and demolition. The definition framework that this thesis will refer to when talking about “net-zero” is the energy and water components of a single building and its site. We can define a net-zero energy building as a building which, on an annual basis, uses no more energy than is provided by the building’s on-site renewable energy sources.²⁷ We also discuss net-zero water and the capture and treatment of that resource. A net-zero water building is a building that captures and treats as much water as it uses on an annual basis without using public water treatment or sewer system resources. It is important to note that these buildings are still connected to municipal power and sewer systems for code and safety reasons, however they do not use them if at all possible.

Another term used throughout this thesis is net-positive, meaning that a building could presumably push across the line from energy- or water-neutral to creating or capturing more energy or water than the building is using on an annual basis, therefore having a positive effect on the supply of energy or water.

Sustainability, for the sake of this paper, is a way of living that supports long-term ecological balance between humans and nature. Sustainable development encompasses not just a single building but the whole community. It is cognizant of not only what resources we use to build, but where they come

²⁵ <https://www.wbdg.org/resources/netzeroenergybuildings.php>, July 18, 2016.

²⁶ Maclay, 17-20.

²⁷ Maclay, 23.

from. For example, it may seem in the spirit of sustainability to source timber only from the most sustainably-managed forest in the U.S., but if that timber is being trucked from Wyoming to be used on a site in Florida, it defeats the purpose and the embodied carbon of the development is not net-zero.

The following section includes a description of all known sustainable interventions broken into four (4) categories: Energy, Design, Materials, and Waste & Water. It is difficult to say the amount of energy reduction that each is responsible for, especially because many of these interventions work within a dynamic, integrated system that makes up a structure. However, as much as possible, we try to give benefits of each system below. Remember, all these systems work differently in different climates, so results will vary from location to location. However software exists that allows for modeling and simulations that will give a better understanding of these interventions in site-specific context.

Energy

The first set of interventions we look at focuses on energy generation and capture on the supply side, and efficient energy use on the demand side. This section will deal mostly with systems, as design interventions will be covered in the following subsection. I will explain both sustainable energy-capture methods as well as the systems to deploy that energy in an efficient manner throughout the buildings in the form of heating and cooling.

Intervention	Design/Service	Performance
Cogeneration (CHP)	Electricity & Heat Generation	90% Fuel Efficiency compared to 30%-45% traditional electric
Thermal Wheel	Energy Conservation & Reuse	85% efficiency in reusing energy from exhaust air
Photovoltaic (PV) Solar Panels	Electricity Generation	22% efficiency in solar energy capture
Solar Furnaces	Electricity Generation	Performance Unknown
Solar Domestic Hot Water Systems	Heating & Cooling	Performance Unknown
Solar Transpired Air Collectors	Heating & Cooling	80% efficiency in thermal energy capture
Wind Turbines	Electricity Generation	50% efficiency in wind energy capture
Tidal Energy	Electricity Generation	Performance Unknown
Geothermal Heat Pumps	Heating & Cooling	15% more efficient vs. natural gas; 80-95% vs. oil/propane
Energy-Creating Smart Elevators	Energy Conservation & Reuse	75% more efficient than hydraulic lifts
Smart Meters & Occupant Behavior	Energy Metering	Varies widely.
Industrial-Sized Batteries	Electricity Capture	Performance Unknown
Chilled Beam Systems	Heating & Cooling	17% to 22% vs. traditional VAV (UK); 7% to 15% (US)
User-Controlled Ventilation Air Diffuser	Heating & Cooling	Performance Unknown
Earth-Tube System	Heating & Cooling	Performance Unknown
Radiant Floor Heating Systems	Heating & Cooling	30% more efficient than forced air heating
Energy-Efficient Plug Load Uses	Electricity Conservation	Up to 90% energy savings

Table 1: Energy System Interventions & Performance

Above is a chart summarizing the interventions, their use, and performance. It lists 17 interventions that are covered here, as well as their energy savings or comparable performance against traditional systems. Performance outcomes range from 7% to 90% energy-efficiency savings.

Cogeneration (Combined Heat & Power)

Cogeneration systems produce both thermal (heat) and electric energy within the same machinery, in addition to cooling through absorption chillers in some systems (sometimes known as trigeneration). These systems range in size, from commercial power plants to units meant to power individual residences. On a commercial real estate scale, a cogeneration system that powers a typical office building or apartment tower is outputting power loads of less than one megawatt (MW). For the same output of useable energy, these systems use far less fuel than separate heat and power (SHP) systems.

Cogeneration systems work by using a fuel source, like natural gas, diesel, coal, etc., to create electricity by powering reciprocating engines or gas microturbines. However, electricity generation creates excess heat that is normally wasted. Cogeneration systems allow that heat to be recaptured and put back into the system through the domestic hot water or space heating systems within the building. These combined heat and power systems have been shown to reach 90% fuel efficiency, and therefore have substantially lower greenhouse gas emissions in producing the same amount of energy compared to other power generation techniques.²⁸

Cogeneration is preferable over traditional power systems for a number of reasons. First, traditional power plants only capture about 50% to 55% of the energy encapsulated within the fuel burned in the form of electricity.²⁹ The rest is wasted as excess heat. Additionally, there are losses associated with the distances traveled through power lines from traditional power plants, through the grid, and to individual buildings. When these two loss factors are combined, the delivered energy efficiency can be as low as 30% to 45%.³⁰ By creating electricity on-site, a building can reduce those losses and thus be more sustainable, cutting down on waste and demand from the public electrical grid. As of 2008, cogeneration only accounted for 9% of total U.S. electricity generating capacity³¹, suggesting that this technology has a lot of potential to grow and therefore cut energy demand from the public grid across the country.

There is research to suggest that other fuel sources could be used to generate combined heat and power on-site. Biomass fuels like wood, or possibly algae in the future, could be used to power these machines. Additionally, multiple fuel source systems have been successfully introduced that can use solar power supplemented by other fuels to the same effect.³² If that supplemental fuel is biomass, then a truly sustainable system has been created to power the building independently. Until then, cogeneration is a step in the right direction toward energy use reduction, although may not be a part of the final solution until it can be fueled entirely by renewable energy sources.

²⁸ <https://www.epa.gov/chp/chp-benefits>, June 29, 2016.

²⁹ Kaarsbaerg, et al., 1.

³⁰ <http://www.c2es.org/technology/factsheet/CogenerationCHP>, June 20, 2016.

³¹ <http://www.c2es.org/technology/factsheet/CogenerationCHP>, June 20, 2016.

³² Yagoub, 1,604.

Enthalpy Wheel

Enthalpy wheels (also known as thermal wheels) are a form of heat exchanger within a building's ventilation system. They can transfer both heat energy and latent (moisture) energy. The wheel is made out of a porous material, sometimes in a honeycomb-type design to create additional surface area for energy absorption and is coated in a desiccant material that acts to affect the humidity of the air. The wheel works by taking energy from exhaust air and transferring it to the incoming supply of air. In heating scenarios, one half of the wheel is exposed to exhaust air, which warms the material of the wheel and absorbs moisture. The wheel is slowly and continuously turned, and the other half of the wheel is exposed to the cooler incoming air supply. That cooler air supply draws the heat out of the wheel and pre-heats the air supply as well as humidifies the cold, dry air.³³ In cooling scenarios, the wheel is just as effective. The exhaust air leaving the building cools the wheel, which then pulls the heat out of the incoming air supply as the wheel turns. It also can draw moisture out of the air as well, which can lead to large energy savings, as dehumidification is responsible for 30% to 50% of the energy costs of air cooling.³⁴

Because of the way the wheels are manufactured and installed, the wheels only transfer thermal and latent energy and do not allow air exchange between the two sources. Seals are set up around the boundaries of the wheel to make sure that no particulates, toxins, or contaminants are transferred into the incoming clean air supply. Thermal wheels can recover up to 85% of the heat from exhaust air supplies, making them an increasingly popular option for air handling systems in today's building environment.³⁵

Photovoltaic Solar Panels

Photovoltaic (PV) solar panels are the most commonly known and used solar collector technology in the built environment. Photovoltaic simply means that the panels can convert sunlight into electricity.

These panels are made up of many smaller photovoltaic cells. Each cell is made up of two layers of semi-conducting material, traditionally silicon. The top layer is treated to create a negative charge and the bottom layer treated to create a positive charge. The disparity in charges creates an electric field between the silicon layers. This electric field reacts with the photons that hit the cell from sunlight, creating a flow of electrons that then follow the path of least resistance. That path is the wiring of the connected cells within the panel, creating an electric current that becomes usable energy.³⁶

³³ http://livebuilding.queensu.ca/green_features/enthalpy_wheel, July 23, 2016.

³⁴ <http://www.dac-hvac.com/energy-recovery-wheels-what-is-an-enthalpy-wheel/>, July 23, 2016.

³⁵ <http://www.reznorhvac.com/en/as/news/product/thermal-wheel-now-seen-highly-economical-form-energy-saving>, July 23, 2016.

³⁶ <http://www.livescience.com/41995-how-do-solar-panels-work.html>, July 4, 2016.

There are a number of factors that affect solar array efficiency. Typical efficiency is somewhere between 16% and 18% in real world applications for today's silicon-based arrays,³⁷ although some lab tests in ideal conditions have shown that the newest silicon technologies could reach up to 25% efficiency.³⁸ Outside of silicon technology, scientists have developed panels with other materials that are 40% efficient in the lab.³⁹ Today's best panels have a real-world efficiency of just above 22%, and these panels are using a new material called cadmium telluride. Researchers believe that efficiency for the newer cadmium telluride cell technology is as much as 30% in real world applications, not just lab tests in ideal conditions.⁴⁰ These cells are also thinner and take less material to produce the same amount of electricity when compared to their silicon-made competitors and are manufactured through a simpler process. This makes them the lowest carbon footprint option of any solar collector. They also perform better than silicon in hot, humid climates and under low-light conditions on cloudy days. All these factors lead experts to believe that it will be the preferred technology of future solar arrays, especially with the new leap in efficiency. Today more than 90% of solar cells are silicon-based, but in the future, the balance of power will shift dramatically with these new technological advances.⁴¹

The factors that greatly affect the efficiency of these panels include: panel orientation, roof and panel pitch, temperature, and shade.⁴² Panels should face south in Northern Hemisphere locations, in order to capture the most direct sunlight throughout the day. The angle or pitch of your panels will also affect how much sunlight they see throughout the day. Commercial systems offer tracking systems that automatically follow the path of the sun throughout the day and adjust their angle. Additionally, solar panels are less efficient if they are overheated, which is why the cadmium telluride panels are gaining popularity. However, a good amount of airflow, with the panels mounted a few inches off the roof can help to keep the units cool. Lastly, shade can be detrimental to a solar array. Because all the panels are linked and make a circuit, even if one panel is in the shade, it can break the circuitry link and negatively impact the entire system.

The use of solar energy is widely regarded as one of the most likely technologies to rival fossil fuel and bring us to a renewable energy fueled future. Even without technological advancement, the industry could reach terawatt scale deployment of solar power by 2050. Couple that with advancements in cell technology using thin-film technologies based on Earth-abundant materials, and the potential impact is

³⁷ <https://www.technologyreview.com/s/600922/first-solars-cells-break-efficiency-record/>, July 4, 2016.

³⁸ <https://www.technologyreview.com/s/600922/first-solars-cells-break-efficiency-record/>, July 4, 2016.

³⁹ <http://pureenergies.com/us/how-solar-works/solar-panel-efficiency/>, July 4, 2016.

⁴⁰ <https://www.technologyreview.com/s/600922/first-solars-cells-break-efficiency-record/>, July 4, 2016.

⁴¹ <https://www.technologyreview.com/s/600922/first-solars-cells-break-efficiency-record/>, July 4, 2016.

⁴² <http://pureenergies.com/us/how-solar-works/solar-panel-efficiency/>, July 4, 2016.

world-changing. Through continued technological advancement, increase in efficiency, and better materials, the industry is hopeful that solar energy can break our dependence on non-renewable energy.⁴³

Solar Furnaces

Another much less frequently used method of capturing solar energy is the solar furnace. A solar furnace uses parabolic mirrors to focus heat and light on one small spot. The goal is to increase the power and intensity of the sunlight many times over.⁴⁴ The heat that is created is used to generate electricity or steam to power generators or industrial equipment. For commercial building applications, the heat could be used to power forced air systems during cold weather. The design includes a series of glass heat concentration tubes that act as solar heat collectors. They each contain a heat-conducting core, like copper, which carries the concentrated heat to a plenum. Then cool air is passed over it and transferred from the plenum to the air.⁴⁵

The world's largest solar furnace can be found in Font-Romeu-Odeillo-Via, a town in the Pyrenees Mountains on the France-Spain border. The furnace is made up of an array of 10,000 mirrors that direct the sun's rays onto a large concave mirror that then focuses all the sunlight onto an area the size of a cooking pot. This area can reach temperatures of above 3,000°C (5,430°F). The heat is then used to generate electricity.⁴⁶

Other applications exist for industrial practices, such as melting steel or making hydrogen fuel or nanomaterials. However, the reliance on uninterrupted sunlight is a limiting factor in their practical application in the built environment. The reason that the site in Odeillo has been successful is that it experiences approximately 300 clear sunny days annually. There are a limited number of places on earth that get that type of sun exposure, so for practical purposes, photovoltaic cells are much more useful for harnessing the sun's energy.

Solar Domestic Hot Water Systems⁴⁷

Another way to capture the energy of the sun is through solar domestic hot water systems. Also known as solar water heaters, they can be a sustainable way to generate hot water for buildings. They can be used in any climate, and exist as both active and passive systems. The system has two parts: storage tanks and solar collectors. The water is pumped through the solar collector which draws the thermal heat

⁴³ <http://www.computerworld.com/article/2919134/sustainable-it/mit-says-solar-power-fields-with-trillions-of-watts-of-capacity-are-on-the-way.html>, July 4, 2016.

⁴⁴ <http://www.solarpoweristhefuture.com/how-a-solar-furnace-works.shtml>, July 4, 2016.

⁴⁵ <http://www.solar-for-energy.com/solar-furnace.html>, July 4, 2016.

⁴⁶ <http://www.atlasobscura.com/places/worlds-largest-solar-furnace>, July 4, 2016.

⁴⁷ <http://energy.gov/energysaver/solar-water-heaters>, June 29, 2016.

of the sunlight into the water to warm it. Two types of active systems include direct circulation and indirect circulation. Direct circulation systems pump household water through the solar collectors and into the home, and work well in climates where the temperature rarely drops below freezing. Indirect circulation systems include a non-freezing, heat-transfer fluid and a heat exchanger. This type of system is popular in colder-weather climates and keeps the system from freezing and becoming incapacitated.

These systems require a well-insulated storage tank to reduce heat loss. Some systems work with a two-tank setup, where the solar water heater preheats the water and then is transferred into a more traditional water heater that heats the water the rest of the way to the optimal temperature. These systems are typically used more in residential buildings, as it is difficult to heat enough water for a large commercial building through this process alone.

Solar Transpired Air Collectors⁴⁸

Transpired air collectors are dark-colored, perforated façades installed on the south-facing walls of commercial or industrial buildings. This technology helps to preheat ventilation air for the building. A gap between the building and the air collector allows for ambient air to be warmed. A fan is used to draw the preheated air into the building's ventilation system through the perforated absorber plate, or façade. The solar energy absorbed by the dark colored, heat conductive surface can preheat the ambient air by as much as 40°F above the outside air temperature.

In heating-dominated climates, this technology can be part of the energy-efficient solution. Research shows that the transpired collector can capture up to 80% of the sun's energy. The systems have no moving parts besides the fan that is part of a normal air handling system and are virtually maintenance free. The system is even helpful at night without sunlight, as it captures heat escaping through the south-facing wall and circulates it back into the building. Favorable conditions for such a system consist of buildings with long south, southwest, or southeast facing façades, long heating seasons, high rates for heating energy, and large ventilation requirements.

Wind Turbines

Wind turbines are another tool to generate renewable energy, by capturing the power of air movement. Wind energy is seen as the other most promising renewable energy technology in today's world, alongside solar. The blades of the wind turbine are shaped like airplane wings, so that the air pressure going over the top and bottom is uneven, and lift is created. This lift creates the movement that is necessary to generate power. Large-scale wind turbines only turn at a rate of about 18 revolutions per minute (RPM).

⁴⁸ <http://www.nrel.gov/docs/fy06osti/29913.pdf>, July, 2016.

However, the shaft that is turned by the blades is connected to a series of gears that increase the RPMs to about 1,800 revolutions, a speed fast enough to power the generator and create electricity.⁴⁹ A small weathervane is attached to a computer system which facilitates the turbine being pointed into the wind, making it as efficient as possible.

There are two main types of wind turbines, horizontal-axis turbines and vertical-axis turbines. The more common form is the horizontal-axis turbine, which has three blades and resembles an airplane propeller. The size of these turbines ranges from 100 kilowatts to as large as several megawatts. The technology is more effective when grouped together in wind farms to supply bulk power to the electrical grid. The efficiency of these turbines has increased dramatically in recent years as the technology improved. In a ten-year time span, load capacity increased from 25% to over 50%.⁵⁰ This means that if maximum capacity of a turbine was 1 megawatt, ten years ago it would be producing on average 250 kilowatts and now it is producing over 500 kilowatts. This advancement in technology is allowing for wind energy to be captured in more places where it may be less consistent or powerful, greatly increasing the total wind power capacity throughout the country and the world. In 2015, wind energy created 7 times the amount of electricity that solar power did, making it second only to hydro power in renewable energy sources⁵¹. In terms of building-level application, hydro power is extremely limited, so wind energy is one of the best options for energy capture for property owners. One example of this is Boston Properties' new building at 888 Boylston Street, which employs several wind turbines on top of its 17-story frame.

One of the next innovations in offshore wind turbines is floating bases. Instead of having to anchor wind turbines to the ocean floor deep below the water, floating wind turbines would be easier to maintain and install, as well as be less costly.⁵² As efficiency increases, wind energy capture will be a more financially feasible technology in the built environment.

Tidal Energy

Another way of capturing energy is through tidal changes, although it is much less prominent than wind and solar. Tidal energy can be generated in three different ways: in-stream devices, barrages, and tidal lagoons. All tidal energy collection methods use generators to produce electricity and capture energy through change in the heights of tides (potential energy) or through the flow of water (kinetic energy). The best locations for tidal energy capture are areas where the tidal range, the difference in height between high and low tide is the greatest. Because water is approximately 800 times denser than air, tidal energy is more

⁴⁹ <http://energy.gov/eere/wind/how-do-wind-turbines-work>, July 5, 2016.

⁵⁰ <http://www.power-eng.com/articles/print/volume-118/issue-3/features/advancements-in-wind-turbine-technology-improving-efficiency-and-reducing-cost.html>, July 5, 2016.

⁵¹ http://www.eia.gov/energy_in_brief/article/renewable_electricity.cfm, July 5, 2016.

⁵² <http://www.gizmag.com/worlds-first-floating-wind-farm/40383/>, July 23, 2016.

powerful than wind energy. Additionally, tides are more predictable and stable, and therefore tidal generators produce a steadier, more reliable stream of electricity. Unfortunately, there are limited sites that are suitable for this kind of energy capture.⁵³

Tidal energy from in-stream devices is generated as currents move the water. The kinetic energy in the movement of such large amounts of water can be captured through turbines. These turbines are most effective in shallow water. In-stream devices are currently the most popular because they are typically removable, can be scaled from single turbines up to arrays fairly easily, and have the smallest potential costs and ecological impact.⁵⁴

Barrages are similar to dams and are located along rivers, tidal estuaries and ocean bays with tide changes, spanning the entire width. This technique captures the potential energy of tidal changes. Gates in the dams are regulated to allow the rising tide to enter a storage area and the falling tide to exit. Energy is generated as the water flows through turbines located at the gates, similar to how a dam in a river would harness hydropower. This type of energy capture has very high costs and is the most harmful to environments because it alters natural patterns of sea life.⁵⁵

Lastly, tidal lagoons operate similarly to barrages with a few differences. They do not extend the full width of a waterway, so they do less environmental damage. They too store the water of the rising tide and then power a turbine as the tide recedes and the water is pulled back out. However, they can also generate power continuously, something that barrages cannot do. They allow for the inflowing water to pass through the turbines to generate additional electricity, basically acting like a combination of in-stream devices and barrages. The increased energy capture and the lack of environmental disruption make tidal lagoons a better option for renewable energy.⁵⁶

This energy source is still very much unproven and in the early stages of development. Currently, the U.S. does not have any tidal energy capture plants and the number of feasible sites given today's technology are few and far between.⁵⁷ As a building owner, locations for this type of renewable energy are extremely limited. Property would have to be located on a waterway with enough tidal change to make the technology effective.

⁵³ <http://nationalgeographic.org/encyclopedia/tidal-energy/>, July 5, 2016.

⁵⁴ <http://fundyforce.ca/renewable-and-predictable/tidal-energy-generation/>, July 5, 2016.

⁵⁵ <http://fundyforce.ca/renewable-and-predictable/tidal-energy-generation/>, July 5, 2016.

⁵⁶ http://greenthefuture.com/TIDALPOWER_HOWITWORKS_LAGOON.html, July 13, 2016.

⁵⁷ <http://nationalgeographic.org/encyclopedia/tidal-energy/>, July 5, 2016.

Geothermal (Ground-Source) Heat Pump or Geo-Exchange System

Another energy source available for capture is the heat of the earth's core. Although geothermal capture through geysers, hot water, and rocks is extremely limited geographically, the latent heat of the Earth can still be utilized at the building level. Geothermal heat pumps take advantage of the naturally-occurring difference between air temperature and sub-surface soil temperature. The Earth's temperature increases at an average rate of 1°F for every 70 feet of depth.⁵⁸ These heat pumps use the relatively more constant temperature of the Earth beneath the surface to regulate building climate in both heating and cooling seasons. The bigger a building, the more bore holes and heat pumps can be used and the deeper those bore holes can be drilled in order to make the most of the geothermal heat.

Geothermal heat pumps are able to utilize ground temperatures between 40°F and 80°F, which remain relatively constant throughout the year below depths of about 30 feet.⁵⁹ The pump system circulates water or another non-freezing liquid to pull heat from the Earth through a closed-loop system, meaning a pipe that goes down into the earth through a bore hole, turns at the bottom and comes back up to the surface in the same bore hole. The liquid is pumped deep within the earth and draws heat from the soil, then returns to the building through the loop with the heated water. It is passed through a heat exchanger that transfers the heat into the building's air handling system.⁶⁰ For cooling, the system can effectively work in reverse. It extracts heat from the ambient air of the building and pumps that warmer water down into the earth to exchange the heat and bring back cooler water.

The system can be used for space heating within a building and/or domestic hot water with the addition of a desuperheater. A desuperheater is another type of heat exchanger that can transfer the heat from the Earth into the domestic hot water system of the building. Heating water through geothermal heat pumps can cost about 80% less in a heating-dominated climate and up to 95% less in a cooling-dominated climate, when compared to electric, oil, or propane-fired water heating systems. When compared to natural gas systems, the savings drops to about 15%.⁶¹

This system can be used almost anywhere in the world and typically the bore holes are between 10 and 300 feet deep, depending on the climate.⁶² These systems use a relatively small amount of energy to operate the pumps. For each unit of electricity used to operate the system, as much as five times as much energy can be delivered from the ground, making the system net-positive.

⁵⁸ <https://www.epa.gov/rhc/geothermal-heating-and-cooling-technologies>, July 5, 2016.

⁵⁹ <http://www.builditsolar.com/Projects/Cooling/EarthTemperatures.htm>, July 13, 2016.

⁶⁰ <https://www.epa.gov/rhc/geothermal-heating-and-cooling-technologies>, July 5, 2016.

⁶¹ <http://www.geojerry.com/desuperheater.html>, July 13, 2016.

⁶² <http://geo-energy.org/Basics.aspx>, July 5, 2016.

Energy-Creating Smart Elevators

One of the newest energy-capturing technologies out there is the smart elevator. Although it will not be a revolutionary energy-capturing technology in terms of pure volume of energy capture, it is another piece to the overall puzzle and an interesting piece of machinery to discuss.

The newest elevator technology is becoming more and more efficient. These elevators now have improved controls, hardware, and systems that both use less energy and actually generate usable electricity. These elevators are also more compact, taking up a smaller portion of the building footprint.

Some of the features that these elevators include: in-cab sensors that enter a sleep mode and turn off lights, music, ventilation, and video screens when empty; software and micro-processor based controls; and smart dispatch control that groups elevator stops for more efficient movements. Another energy saving feature seen in some new designs is the double-stacked elevator cab, one cab stopping at only even-number floors and the other at odd-numbered. They can reduce the overall energy use by reducing the total number of stops and starts throughout the day, conserving momentum.⁶³

The most exciting hardware advancement is the invention of regenerative drives that recycle energy rather than wasting it in the form of heat. These magnet motors are capable of bidirectional energy flow. When power flows into the motor, it creates torque that lifts the elevator. When the cab travels downward, the motor instead acts as a generator, transforming mechanical energy into electrical power and sending it back into the building's energy grid, similar to how electrical motors and batteries on newer electric cars recapture energy as the car breaks. When an elevator travels upward with a light load and downward with a heavier load, it actually creates more energy than it uses within the context of that roundtrip.⁶⁴

The most energy-efficient type of elevator today is the machine room-less traction elevator. These new elevators are designed to take all the equipment that traditionally needed to be housed in a separate space and incorporate it into the elevator shaft itself. This space-saving design eliminates the need to build and supply energy to an extra room in the building and therefore consumes significantly less energy than its older counterparts. For example, the Otis Gen2 elevator is up to 75% more energy-efficient than traditional hydraulic lift systems and uses up to 40% less energy than even new non-regenerative machine room-less systems.⁶⁵

Again, elevator technology is not going to revolutionize the built environment, but it is a step in the right direction. By reducing overall gross square footage, increasing building footprint efficiency, and reducing overall energy use, smart elevators are another part of the solution.

⁶³ <https://www.asme.org/engineering-topics/articles/elevators/energy-efficient-elevator-technologies>, July 5, 2016.

⁶⁴ <http://www.otis.com/site/us/Pages/Gen2ProductPage.aspx>, July 6, 2016

⁶⁵ http://www.otis.com/site/us/OT_DL_Documents/OT_DL_DownloadCenter/Gen2%C2%AE%20-%20Product%20Information/Gen2%20Brochure.pdf, July 6, 2016.

Smart Meters & Occupant Behavior

Capturing energy in new, sustainable ways is one of the main pieces to net-zero design. But another major contributor is the efficient use of that energy. That is why information is key to this process. If building occupants are informed of the consequences of their behavior in real-time, that behavior has the ability to be altered. That is where smart meters will make their contribution to the net-zero mission.

Smart energy meters are replacing traditional analog meters that historically were checked by meter readers on a monthly basis, with bills delivered post-energy consumption. These new smart meters can wirelessly transmit energy use data to the utility companies and building users in real-time to help create a smarter grid. Energy use data is available to the occupant in time intervals as small as 15 minutes.⁶⁶ Originally, the hope was that by informing consumers, behaviors would change and people would start to make adjustments to save money. This adjusted behavior would in turn balance energy use on a macro-level scale, with more people opting to consume energy during off-peak hours, saving money, and taking energy burdens off the system during traditional high demand periods. However, that would require variable pricing based on peak energy times as well as informed consumers. As of early 2015, only about 8 million Americans had access to these variable, or “smart pricing” electric costs.⁶⁷

In reality, the changes seen since the installation of more than 50 million of these devices are underwhelming. Utility companies have failed to educate end users of the benefits, and in-home displays for smart meters are almost non-existent, so real-time learning is not happening.⁶⁸ The biggest miss for this technology is the lack of a user interface. Users cannot adjust behavior if they are not seeing the effects of that behavior. Additionally, because most users are paying a flat rate for per-watt energy, they are not incentivized to adjust their behavior.

One of the biggest ways to save energy in the built environment is to educate building users about how their behavior effects the energy use of the building as a whole. Small changes made by 1,000 occupants of an individual office building over the course of the year can add up to large savings. Smart metering and variable pricing strategies coupled with daily reporting have the possibility to go a long way to adjusting occupant behavior. According to a study by the Smart Grid Consumer Collaborative, only 8% of smart reader users were using “online analysis for their specific energy use” like web portals that were provided by the energy companies.⁶⁹ And according to a study conducted at the University of California

⁶⁶ <https://www.washingtonpost.com/news/energy-environment/wp/2015/01/29/americans-are-this-close-to-finally-understanding-their-electricity-bills/>, July 6, 2016.

⁶⁷ <https://www.washingtonpost.com/news/energy-environment/wp/2015/01/29/americans-are-this-close-to-finally-understanding-their-electricity-bills/>, July 6, 2016.

⁶⁸ <http://smartgridcc.org/wp-content/uploads/2013/11/SGCC-Consumer-Pulse-Wave-4-Summary-Report.pdf>, July 6, 2016.

⁶⁹ <http://smartgridcc.org/wp-content/uploads/2013/11/SGCC-Consumer-Pulse-Wave-4-Summary-Report.pdf>, July 6, 2016.

at Davis, the combination of smart meters with variable pricing, alerts for high-cost energy use periods, and in-home displays resulted in participants saving between 11% and 14% compared to the control group who just had smart meters.⁷⁰

Changing user behavior combined with smart grids and metering has the potential to change how occupants use energy and how they think about that energy use. The tools are in place to make us more informed users of energy and technology. Part of the solution is reliant on the population to realize its impact and to adopt a new normal for energy use patterns and behavior.

Industrial-Sized Batteries

Many of these renewable energy sources have great potential but they lack consistency. For sources like solar and wind, electricity is only available when the sun is shining or the wind is blowing. They can only be used when those energy sources are actively producing energy. These energy sources are considered variable, affected by time of day, weather, and location. There is no cost-effective way to capture and store the energy for later use. However, as battery technology improves and cost declines, there will be a way to harness that surplus energy that is not immediately used. And as newer, more efficient renewable energy sources are developed, this battery technology will become more valuable.⁷¹

Industrial-sized batteries work the same way traditional batteries work, by taking electricity and converting it into chemical potential energy and then back into electrical energy as needed. For buildings with renewable technology, they can smooth out the variability of the flows of energy and store the excess energy that is created during ideal solar and wind conditions. Currently, these fluctuations are handled by supplementing renewable energy sources with non-renewable energy sources like fossil fuels.

Buildings will be able to get closer to energy-independent by increasing their renewable energy footprint and capturing energy to be used throughout the day, while no longer having to fall back to the public grid. Batteries are one of the most exciting renewable technologies that could be hugely effective at the building scale. Tesla is already selling the Power Wall, a home-battery that allows storage and off-peak charging for efficient energy use. This battery technology could allow residences to go net-zero in the very near future.⁷² As the concept is proven in residential development, the adoption rate could increase drastically and greatly reduce public grid demand, shifting the country into a new phase of energy use and creation.

Some of the challenges with the current battery technology include safety, sustainability and cost. Many chemicals used in batteries are at risk of overheating and starting fires and are not recyclable once

⁷⁰ Jessoe, 1,436.

⁷¹ <http://www.ecowatch.com/how-better-battery-storage-will-expedite-renewable-energy-1882097909.html>, July 6, 2016.

⁷² <https://www.teslamotors.com/powerwall>, July 5, 2016.

the battery has outlived its useful life.⁷³ Additionally, the efficiency and charging speed is still improving to a point where they are economically feasible. All this new technology is always costly as it is developed, but continued advancement will make the batteries safer, more efficient, and cheaper. Battery technology and efficiency has improved at a similar rate to solar technology,⁷⁴ so the future for their combined use is bright.

Chilled Beam Systems

Now that we have looked at energy capture, energy metering, and storage potential, we will look the systems using that energy more efficiently. The first system we describe is the chilled beam system for air cooling within a building. There are two types of chilled beam systems, passive chilled beam systems and active chilled beam systems. This section focuses on active chilled beam systems, as they are the most widely used and offer more reliable cooling potential.

Active chilled beam (ACH) systems are made up of a fin-and-tube heat exchanger and a primary air source, located in the ceiling of each level of a building. Cold water is pumped through the heat exchanger and cools the air passing over the tubes. Because hot air rises, the warmest air is typically cooled first, and then gravity carries the denser, cooler air downward, creating natural circulation. The system is supplied with primary air from a centralized system, which also helps to meet the fresh air requirements of building codes, LEED certifications, etc. This primary air source can be dehumidified to meet the appropriate moisture content that will offset the humidity of the existing air in the space. This brings the dew-point temperature of the room down to prevent condensation on the surfaces of the chilled beam.⁷⁵

One benefit of this type of system is water can carry much more energy than the same amount of air, so chilled beam systems are much smaller than traditional air duct systems. Because of this, floor-to-floor heights can be reduced, leaving the potential for more efficient building design in cases where height restrictions are in place. Or floor-to-floor heights can remain the same, but less space is taken up at the ceiling, making for more usable volume and additional daylight at the window line.

According to a 2013 study commissioned by the Chilled Beam and Ceiling Association (CBCA) and carried out independently by Environmental Design Solutions Ltd., chilled beam systems produced between 17% and 22% energy cost-savings when compared to the variable-air-volume system against which they were tested. They also performed favorably in terms of CO₂ emissions and overall energy

⁷³ <http://www.ecowatch.com/how-better-battery-storage-will-expedite-renewable-energy-1882097909.html>, July 6, 2016.

⁷⁴ <http://www.bloomberg.com/news/articles/2015-05-06/tesla-s-new-battery-doesn-t-work-that-well-with-solar>, July 5, 2016.

⁷⁵ <http://www.cibsejournal.com/cpd/modules/2014-06/>, June 29, 2016.

consumption. The study used average weather data over the last 20 years in London and Birmingham in the United Kingdom, and the performance of four sample office buildings with different sizes and layouts.⁷⁶

However, there is some argument over whether chilled beam systems are actually more efficient than newer, more energy-conscious variable-air-volume (VAV) systems. When running at full capacity, the energy loads to push source air and water supply for chilled beam systems are much less than the energy load of a VAV system. But VAV systems can pull back from full capacity when maximum cooling is not needed, whereas ACH systems keep a continued air flow at all times.

Another difference of the systems is the temperature of the cold water that circulates and cools the air. Because VAV systems are centrally located in mechanical rooms and have to cool large volumes of air at once, water temperatures in these systems are lower, requiring more energy to cool that water. However, for ACH systems, the water cannot fall below the dew-point temperature of the surrounding air because it would cause condensation within the space, so the water is only cooled to between 56° and 60°F. Because of the warmer temperature, water pumps have to circulate more water through ACH systems at faster speeds, using more energy. In addition, because of the condensation problem, air inside the building has to be dehumidified to avoid moisture infiltration, which can also consume energy that VAV systems do not.⁷⁷

With all these considerations, it depends on the climate and location of the project as to whether a chilled beam system is the right choice. In simulations, new chilled beam systems are between 7% and 15% more energy efficient compared to VAV systems in various locations in the U.S.⁷⁸ However, newer, more efficiently designed VAV systems have been tested to be more energy-efficient than ACH systems in certain locations as well, so simulations are needed to make the best choice for a specific site.

User-Controlled Ventilation Air Diffuser⁷⁹

Air diffusers are the grates that supply ventilation air from the ceiling of most office buildings using variable-air-volume systems mentioned above. Often, office floors are grouped into zones and cooled or heated all the same way, from offices to conference rooms to open cube formations. However, as we see in many office settings, different people have different preferences. Oftentimes some people are rolling up their sleeves in the summertime while others are hiding beneath sweaters. New air diffuser technology now exists that incorporates a microprocessor controller that can monitor the temperature of the space within which it is circulating air. As conditions vary, the diffuser can adjust airflow and supply to a particular space. In addition to sensors that monitor the comfort level of the space, users can manually adjust diffusers

⁷⁶ Gaskell, 9.

⁷⁷ Murphy, et. al, 3-6.

⁷⁸ Murphy, et. al, 8.

⁷⁹ <https://www.priceindustries.com/products/details/prodigy-controls>, July 7, 2016.

in their space by increasing or decreasing airflow. These adjustments allow the system to work at less-than-full capacity at times where individual occupants are being overheated or overcooled by the system. This technology is fairly new and few models exist that allow for user controls, therefore data does not exist as to the energy savings realized by this intervention. Additional research will be needed in the future as these systems are more widely implemented.

Earth-Tube System

Earth tube systems are a way to provide 100% fresh ventilation air to smaller buildings with less energy use by shielding the incoming ventilation air from either extreme hot or cold conditions. The tubes are buried within a few feet of the surface of the earth, and the soil shields the tubes from temperature extremes during the hottest and coldest months of the year. Fresh air enters the series of pipes that are embedded in the interior of the foundation from intake portals at the Earth's surface, absorbing energy from the surrounding soil, and thus moderating the temperature of the fresh air. These systems are then fed into the normal air ventilation system of the building where the air is heated or cooled to the desired temperature. The necessary temperature change is lessened and allows for less energy to be used.⁸⁰

In the earliest days of these systems, there were issues with air quality, moisture, mold, and harmful gasses infiltrating the home. Today, more efficient and healthier systems have been developed and processes have been improved to create better quality earth tube systems. One example is the ERV system from UltimateAir, which not only claims to circulate fresh air and push stale air out of the home, but also states that 95% of the energy within the house to heat or cool the space is retained through their technology, which utilizes enthalpy wheels.⁸¹ Although this is an interesting passive technology, it is more meant for residential development and is not very common within the built environment.

Radiant Floor Heating Systems

Radiant floor heating systems are one of the most energy-efficient ways of heating a structure. They come in either electric or hot water. The electric version uses zigzagging loops of resistance wire underneath the floor and radiates heat through the flooring, usually retrofitted to a single room like a bathroom or a kitchen. The more popular design is the hot water system. Typically, half-inch PVC pipes are housed within the floor, either on top of the subfloor in grooved panels, clipped into aluminum strips on the underside of the floor, or embedded in poured concrete. The last option, embedded in the concrete slab, is the most cost- and energy-efficient.⁸²

⁸⁰ <https://www.thenaturalhome.com/earthtube.htm>, July 6, 2016.

⁸¹ <http://www.ultimateair.com/>, July 13, 2016.

⁸² <http://www.thisoldhouse.com/toh/article/0,,1548320,00.html>, July 8, 2016.

The system works by circulating hot water through the pipes underneath the floor and radiating heat up through the room. The layout throughout the entire floor allows for evenly dispersed heating and does not leave cold corners or rooms. Because the heat radiates through objects, it heats everything it touches, from the legs of the kitchen table, to the couch, to the coffee table. Because everything in the room is being heated at the same temperature, furniture and fixtures do not draw heat out of the body when they are touched. Additionally, the heat is rising from the bottom of the room to the top at a slow pace, meaning the space that is being heated is where the people actually are.⁸³

In traditional VAV systems, air blows until the air in the room reaches the temperature set by the thermostat. However, that air moves quickly to the ceiling, as hot air always rises. Furthermore, the furniture in the room sucks heat out of the air, cooling the room closer to the floor. Then, the air handling system has to turn back on, ramp up, and reheat the air even though the air at the ceiling is still well above the desired temperature. Your forehead may be perspiring as your toes feel uncomfortably cold. Radiant heat systems avoid this problem.

In addition to a more comfortable system, radiant heat systems can be up to 30% more efficient than forced air heating.⁸⁴ The one drawback to radiant heat system is the need for a separate cooling system, but in climates that are heating intensive, the tradeoff may be worthwhile.

Energy-Efficient Plug Load Uses

So far we have discussed energy capture, energy-intensive systems, and human behavior within the spaces we occupy on a daily basis. Another thing to be aware of is the behavior of the machines that occupy that space with us. One of the easiest ways to make a building more efficient is to reduce the electric plug loads within the building. Residential and commercial buildings have kitchen appliances, light bulbs, computer and office equipment, etc., that all use energy constantly throughout the day.

In the U.S., office equipment directly consumes 7% of total commercial electric energy at a cost of \$1.8 billion annually. Using the latest technology that has been certified as energy-efficient by rating agencies like ENERGY STAR helps reduce the electric load on a building. Energy-efficient “smart” power strips that can regulate energy consumption also cut down on wasted energy while electronics sit in idle mode. ENERGY STAR-rated office products can save as much as 90% of the energy consumed by non-efficient products⁸⁵. Artificial lighting is another huge user of energy in commercial buildings. LED (light emitting diodes) light bulbs create only 10% of the carbon dioxide emissions of incandescent light bulbs and 43% of CO₂ emissions of compact fluorescent bulbs (CFL’s).⁸⁶

⁸³ <http://energy.gov/energysaver/radiant-heating>, July 8, 2016.

⁸⁴ <http://www.thisoldhouse.com/toh/article/0,,1548320,00.html>, July 8, 2016.

⁸⁵ <https://www.myenergysolution.com/energy-saving-products/homeoffice.html>, July 4, 2016.

⁸⁶ <http://www.designrecycleinc.com/led%20comp%20chart.html>, July 4, 2016.

Another consideration is the over-performance of the office equipment that companies employ. Many typical office electronics are more powerful than they need to be for the purpose that they are serving and therefore waste electricity. For instance, computers with high-end processors and graphics cards being used by an employee who typically uses simple Excel sheets, does research using the internet, and communicates over a simple email system are an inefficient use of resources. An energy-efficient computer with a mid-level processor would use much less energy over the course of a year. In a 250,000 square foot office building with 1,000 employees each using a computer, the energy savings can be significant. LEED-certified buildings are able to reduce their electrical consumption by 25% or more and plug load use is one of the biggest factors.⁸⁷

As you can see, any number of combinations of the interventions above would allow a developer and building owner to significantly reduce the amount of energy that a building uses from the public electrical system. Through energy capture, efficient systems, and thoughtful occupants, positive strides are well within reach.

Design

The next category of interventions falls into the realm of building design. Some of the following elements are physical design choices, like building alignment and ventilation strategies while others are either purposeful exclusions or thoughtful inclusions like car-free buildings or bike rooms and showers. They all in some way, shape, or form contribute to energy-efficiency, either at the site or within the surrounding community. This is where the creativity of architects and the thoughtfulness of passionate developers shine through.

On the next page is a chart summarizing the design interventions and their performance. They range in uses from energy conservation to air quality. Performance-wise, outcomes range from 1.5% energy reduction up to 75% energy conservation.

⁸⁷ <http://www.usgbc.org/articles/green-building-facts>, July 13, 2016.

Intervention	Design/Service	Performance
Irresistible Staircase/Elevator Location	Electricity Conservation	75% of vertical trips used stairs - Bullitt Center
Passive Solar Design	Climate Control; Lighting Efficiency	Results vary
Natural Ventilation Layouts	Climate Control; Energy Conservation	Results vary
Revolving Doors	Energy Conservation	Reduce energy consumption for heating & cooling by 1.5%
Tight Building Envelope	Energy Conservation	Reduce energy use from 25% to 40% in SF-residential
Daylighting/Natural Light Elements	Energy Conservation; Lighting Efficiency	Can reduce energy load from lighting between 50% and 80%
Upturned Beam Design	Lighting Efficiency	Performance unknown
Green Roofs	Energy Conservation	Can reduce cooling demand from AC by over 75%
Green/Living Walls	Energy Conservation; Air Quality	Results vary
Reflective Surfaces/Cool Roofs	Energy Conservation	Can reduce AC energy load by 15% for single-story building
Car-Free Buildings	Reduce transportation energy	Results vary
Bike Storage Rooms	Reduce transportation energy	Results vary

Table 2: Design Interventions & Performance

Irresistible Staircase/Elevator Location

The irresistible staircase is a term coined by the development team that built the Bullitt Center in Seattle, Washington. What it refers to is a staircase that is designed well enough and placed prominently enough in the building that people use it significantly more frequently than they use the elevator. In a typical office building, occupants use the stairs somewhere between 17% and 23% of the time. In the first year of occupancy at the Bullitt Center, people used the staircase for 75% of their vertical trips.⁸⁸ Not only did the beauty of the staircase help, but the building design also facilitated this change in behavior. While the staircase is the first thing you see when you walk into the building, the elevator is tucked away in a far back corner and requires a keycard to access.

Another feature of an irresistible staircase is its ventilation and ease of ascension.⁸⁹ The staircase should be well ventilated and have air movement to keep users cool. The staircase can act as a ventilation shaft and let hot air vacate the building through the top while pulling cooler air in at the ground level during cooling-heavy times of the year. In the heating-dominated seasons, less heat is needed because people will be exerting energy to make the climb. In terms of the ascension, a more gradual slope from shorter step heights and large landing spaces allow for less exertion for climbers as well as places for people to stop, enjoy the view, have a conversation, or rest. Avoiding congestion is key as well. Having large landing areas and wide stair widths eliminates a feeling of being crowded or cramped on the stairway, which would dissuade people from using it. This seemingly simple design intervention has been proven to increase occupant health, reduce energy use, and create a more dynamic and collaborative working environment.

⁸⁸ <http://www.scientificamerican.com/article/architects-place-priority-on-public-health-for-2015/>, July 8, 2016.

⁸⁹ Thomas, 105, 114.

Passive Solar Design

There are many pieces that make up passive solar design, using various methods to make the most out of the sun's heat and light. The design strategy is implemented in three ways: building orientation, thermal massing, and passive shading.

Building Orientation: Building orientation is the most important element of passive solar design. The building's long axis should run in an east-west orientation so that the north and south sides of the building get the most sun exposure. Assuming we are in the Northern Hemisphere, passive solar design takes advantage of windows on the south-facing side of the building, and for the best results windows should face within 30° of true south. When selecting a site, it is important to think about the uses to the south of your site. For the best outcomes, an unobstructed view is needed for sun exposure.⁹⁰

Thermal Mass: Thermal mass is responsible for absorbing and holding heat. The materials typically used include concrete, brick, stone, and tile. Thermal mass absorbs heat from sunlight during the heating season (winter) and absorbs heat from the warm air in the house in the cooling season (summer). Objects with a high thermal mass can regulate a structure's temperature because they do not allow as much heat into the space during the day and do not allow as much heat out when the temperature drops at night. Thermal mass is able to reduce the swings in temperature throughout a 24-hour cycle. It is most useful in places where there are large temperature swings from day to night, like desert climates. In climates where the average daily temperature is either above or below the comfort range, thermal mass is actually detrimental to the inhabitants of the structure, so it is important to match building design to climate.⁹¹

Passive Shading: Passive shading is another term for an overhang or awning. Passive shading is a crucial element in passive solar design because it blocks the sun's heat when it is least desired. In the summer, when the sun is high in the sky and the building needs to stay cool, the awning protects the south-facing window glazing from solar radiation and heat gain. It also keeps the thermal mass in the shade, and therefore keeps the house cooler. In the winter the overhang lets the light in through the south-facing windows to warm the building. This angular change is created by the tilt of the Earth's axis as it rotates around the sun. The path of the sun is lower in the winter sky and therefore the sunlight is able to penetrate the windows at an angle below the overhang.⁹² It is these small intricacies that make passive solar so interesting. Little design elements can make a large impact on the built environment, but only if the decision makers involved are aware of them.

⁹⁰ <http://energy.gov/energysaver/passive-solar-home-design>, July 8, 2016.

⁹¹ <http://sustainabilityworkshop.autodesk.com/buildings/thermal-mass>, July 8, 2016.

⁹² <https://greenpassivesolar.com/passive-solar/building-characteristics/overhang-solar-control/>, July 8, 2016.

Natural Ventilation Layouts

Another passive technology in the built environment is natural ventilation, also known as passive ventilation. This type of design takes advantage of natural outside airflow and pressure differences to both cool and ventilate a structure. It can contribute to energy savings by reducing the amount of cool air production from mechanical systems as well as eliminate or reduce the energy load of fans. Natural ventilation as an alternative to traditional air-conditioning units can save anywhere from 10% to 30% of total energy consumption within a building.⁹³ A general rule for natural ventilation is to align the longer axis of the building perpendicular to the prevailing direction of the wind in the summer, which will maximize natural ventilation potential in the summer, fall, and spring. Although solar gain and daylighting should be considered before wind direction, building orientation for ideal solar conditions can be rotated as much as 30° from due south with little impact.⁹⁴

Natural ventilation can be looked at as a circuit, which must be fully completed for the most efficient airflow, needing supply and exhaust openings. This design can be accomplished through open floorplates, transom windows above doorways, louvers and grills. Because hot air is less dense and rises, natural ventilation takes advantage of openings at different levels of a building.

Wind studies can be conducted to model typical airflow at the site. Putting openings on the windward side (the side of the building being hit by the wind) and exhaust exits on the leeward side (the opposite side of the wind) allows air pressure to easily ventilate the building.⁹⁵

Solar chimneys are another technique that can be used to create airflow. A solar chimney is made of a dark colored material that is located at the top of a structure. The dark-colored mass experiences solar gain and heats the air within in the chimney to a temperature that is warmer than the outside air, forcing the air to rise up and out of the building. The air then must be replaced by the vacuum that has been created, and cooler air is pulled in from openings lower in the building structure. This creates a circuit of air movement, naturally ventilating the building.

Another new technology out of Germany, explained in more depth in the Bullitt Center case study, is a window system where the glass automatically pops out when the temperature difference between inside and outside air reaches a certain user-set point, known as parallel displacement windows. The vertically tall windows pop out parallel to the building, allowing for a uniform gap all the way around the glazing. Cool air is drawn in through the end of the window closest to the floor and hot air escapes through the edge of the window closest to the ceiling. These windows have been shown to provide 100% fresh air ventilation to the building.⁹⁶

⁹³ <https://www.wbdg.org/resources/naturalventilation.php>, July 7, 2016.

⁹⁴ <https://www.wbdg.org/resources/naturalventilation.php>, July 7, 2016.

⁹⁵ <https://www.wbdg.org/resources/naturalventilation.php>, July 7, 2016.

⁹⁶ Thomas, 130.

In terms of comfort for building occupants, it is important to note that moving air can give a feeling of cooling, just like a fan does not actually cool the air, but helps whisk away perspiration, which makes us feel cooler. An air speed of 160 feet per minute can decrease the perceived interior temperature by as much as 5°F.⁹⁷ Therefore, a building can actually maintain a warmer temperature, use less energy, and still provide occupants with the same level of comfort and healthier breathing air. However, just like a fan, natural air movement is ineffective at reducing humidity, so natural ventilation strategies are less effective in humid climates.

Revolving Doors

Another technology that takes advantage of air pressure and natural ventilation is the revolving door. Because of the air pressure differences created by tall buildings, openings at the bottom can create large leaks when kept open. When swing doors are opened, air rushes in. On most days, the outside temperature is not ideal, and therefore energy is needed to either heat or cool that outside air that has now penetrated the building. Regular foot traffic in a large downtown office building can cause up to 30,000 cubic feet of conditioned air per minute to leave the building with typical doorways.⁹⁸

However, revolving doors allow a seal to remain while the door spins and lets occupants in and out of the building. A much smaller amount of outside air is introduced into the building through revolving doors, and analysis has shown that eight times more air volume passes through a building when traditional swinging doors are used compared to revolving doors. According to analysis by MIT's Office of Sustainability, the use of revolving doors could save more than 75,000 kilowatt hours of energy.

Apparently though, the hardest part is convincing people to use the revolving door. In MIT's research, they found that just 23% of visitors were using the revolving doors initially and even through an awareness campaign, that percentage never rose above 63%. If 100% of people used the revolving doors on every trip into and out of the building, there would be an annual energy consumption savings on heated and cooled air of 74%.⁹⁹ This could have an enormous impact on energy usage, for such a small design element. Although the technology has been around for more than 100 years, the hardest part about it is its utilization. Again, occupant behavior plays a huge roll in combatting energy waste in the built environment.

⁹⁷ <http://sustainabilityworkshop.autodesk.com/buildings/natural-ventilation>, July 7, 2016.

⁹⁸ http://www.slate.com/articles/health_and_science/the_green_lantern/2008/07/are_revolving_doors_more_energy_efficient.html, July 9, 2016.

⁹⁹ <http://www.hortondoors.com/learning-center/Documents/MIT%20Revolving%20Door%20Energy%20Study.pdf>, July 14, 2016.

Tight Building Envelope

Proper ventilation can only be achieved if the air is coming in and out of the building only from the places intended. A building envelope is the part of the structure that separates the outside unconditioned air from the inside, conditioned air. The envelope is made up of the foundation, walls, and roof, all working together to keep the outside elements at bay. A tight building façade means that the building is air-tight, sealed at all possible leakage points such as joints, between building materials, gaps around doors and windows, penetrations for piping, wiring and ducts, etc. In single-family residential development, leakage in the building façade can account for anywhere from 25% to 40% of the energy used for heating and cooling the space.^{100 101}

The benefits of a tight building envelope go beyond energy efficiency and include improved comfort, improved air quality, a decrease in condensation issues, and decreased obsolescence. A tighter envelope decreases unwanted airflow, drafts, noise and moisture entering the house. It also improves air quality by keeping out pollutants, dust, allergens and radon. In more humid climates, moisture can enter through cracks and unsealed areas of the building and cause mold and mildew problems, which are costly financially and from a health perspective. A tight façade eliminates or greatly decreases these problems.¹⁰²

Daylighting/Natural Light Elements

Daylighting is the controlled admission of natural light through design penetrations within the built space.¹⁰³ It includes the combination of window glazing, window location, natural light elements like skylights, and interior design that allows the most possible natural light into the building. Again, building orientation is important as north and south facing facades experience the most light throughout the day, while west- and east-facing sides only experience sunlight at the beginning and end of the day and at harsh angles that create glare. It is important to note that there is a difference between true or solar north, and magnetic north. When determining building orientation for daylighting, it is solar north that is important to the building alignment and not magnetic north.¹⁰⁴

Many elements come together to create productive daylighting design. First, window glazing is important because direct sunlight can cause overheating within the building, so the right type of glass is necessary. Windows with a low solar heat gain coefficient are needed so minimal heat is let in through the glass but the light still passes through. Also, the depth of the space and the layout are important. Many buildings that have mastered daylighting have large central penetrations that allow light to reach the interior

¹⁰⁰ https://www.energystar.gov/ia/home_improvement/home_sealing/AirSealingFS_2005.pdf, July 8, 2016.

¹⁰¹ <http://www.ubuildit.com/tight-building-envelope-what-it-is-and-why-you-want-one/>, July 8, 2016.

¹⁰² https://www.energystar.gov/ia/home_improvement/home_sealing/AirSealingFS_2005.pdf, July 8, 2016.

¹⁰³ <https://www.wbdg.org/resources/daylighting.php>, July 9, 2016.

¹⁰⁴ Maclay, 67-68.

of floors and not just light gain from the exterior façades of the building. In addition, wide open floor plates help make the most of daylight, not letting office walls and other obstructions block the sun's rays. Reflective, light colored surfaces also help take advantage of the light by multiplying its effects throughout the building.¹⁰⁵

More advanced lighting elements have been developed to help increase the use of daylight in buildings as well. Light shelves have two benefits to building occupants. They are placed at a level that is above the line of sight but below the ceiling on the inside of the building. For those occupants that are seated close to the window, they reduce glare from direct sunlight. However, the top of the overhang is coated with a reflective surface that bounces that light back toward the light colored ceiling, further reflecting it into the space. The reflective surface is typically painted with a bright color or is made out of a reflective material like stainless steel or even mirrors. The next generation of light shelves being explored are able to automatically adjust their position based on the time of day and year to best maximize light. Another light-enhancing feature is the light pipe. A light pipe consists of an external transparent dome, a reflecting metal pipe and a diffuser installed in the ceiling. The dome collects and magnifies external daylight which is then transmitted through the metal pipe, reflecting and multiplying further as it travels to the diffuser, which then distributes diffused daylight to the internal spaces below. State-of-the-art light pipes are using fiber optics to reduce light loss over long distances and allowing these penetrations to benefit multiple floors.¹⁰⁶

Natural daylighting can be a large contributor to the reduction in energy use. The USGBC estimates that energy use from lighting can be reduced by as much as 50% to 80% by a well-designed daylight-lit building.¹⁰⁷ The Department of Energy's Federal Energy Management Program states that these methods can significantly cut energy use due to lighting loads, sometimes up to 75% or 80%. The Federal Office Building in Oakland, California reported that their energy use for lighting was reduced by 86% due to daylighting design interventions and also reduced their cooling energy load by 24%.¹⁰⁸ All these statistics add up to show that daylighting is one of the most valuable ways to reduce energy use and does not require very advanced technology in most cases.

¹⁰⁵ <https://www.wbdg.org/resources/daylighting.php>, July 9, 2016.

¹⁰⁶ <http://www.climatetechwiki.org/technology/daylight-harnessing>, July 9, 2016.

¹⁰⁷ <http://www.climatetechwiki.org/technology/daylight-harnessing>, July 9, 2016.

¹⁰⁸ http://www.solatube.com/sites/default/files/field/files/tech_resources/daylight-facts-figures-energy-saving.pdf, July 9, 2016.

Upturned Beam Design

The following design intervention is a way to increase the daylighting effects just touched upon. There are many ways to frame a multi-story building. Most traditionally, the floor slab sits on top of the cross T-beams leaving 12 to 18 inches of steel facing downward from the surface of the floor slab of the story above. Because of this design, where the building envelope meets the steel beams, the beam obstructs the view at the top of the window line from the inside of the building. An inventive way to avoid this and create taller window heights, and therefore more daylight penetration, is the upturned beam design. The upturned beam is an inverted T-beam. Its use requires considerably more concrete and is thus more costly than traditional construction.¹⁰⁹

With the beam inverted, the bottom of the floor slab and the bottom of the inverted T-beam are flush at the ceiling. Where the ceiling meets the façade, this design has now created an additional stretch of window that is unobstructed, where traditionally, the bottom of the T-beam would be in the way. The obstruction now exists at the floor level of the next story of the building. With this design, light is allowed to penetrate further into the building, allowing for less artificial light to be used in the interior space.¹¹⁰

This intervention was utilized at the Bullitt Center and allowed for an additional eight inches of unobstructed window glazing, but it is something that does come with a cost premium as well as a level of expertise that requires a talented team of engineers and construction personnel.

Green Roofs

Now, to change gears from letting daylight in to keeping it off one of the hottest parts of the building. Green roofs can be constructed on most buildings with a flat top. They consist of a rubber-like waterproofing membrane, a filter layer, a drainage layer, a water retention layer, a layer of nutrient soil and planted vegetation on top. Oftentimes, mosses or sedum are used because they have shallow roots and are easier to maintain, although green roofs can consist of all types of flora, depending on the strength and weight-bearing capacity of the roof and structure. A tertiary benefit of these systems is the extended life of roof membrane systems, shielding them from large temperature fluctuations that can cause micro-tearing and ultraviolet radiation, and therefore require less frequent replacement.¹¹¹

There are many benefits that green roofs provide, both in terms of energy and the environment. First, they are a great way to manage stormwater and unburden the public drainage system. The soil level of a green roof is able to hold between 70% and 90% of all precipitation in the summer months, which is then taken up by the plants and returned to the atmosphere through evaporation or transpiration.¹¹²

¹⁰⁹ Young, 2009.

¹¹⁰ Thomas, 91.

¹¹¹ <https://www.renewableenergyhub.co.uk/how-do-green-roofs-work.html>, July 8, 2016.

¹¹² <http://www.greenroofs.org/index.php/about/greenroofbenefits>, July 8, 2016.

Another benefit is the reduction of heat energy that large urban areas absorb in the warm months. The vegetation absorbs the light and uses it as food, instead of that solar energy being converted into heat energy when it hits the dark-colored rooftops. Absorbing this heat and cooling the roof reduces the amount of energy that the building systems will have to use to cool the building. The vegetation basically acts as a shield from solar heat gain. Roofs are the single greatest source of heat loss in the winter and heat gain in the summer. Research by the National Research Council of Canada found that an extensive green roof reduces the daily energy demand from air conditioning by over 75%.¹¹³

Other benefits include the ability to clean the air and improve air quality. The plants can take in airborne pollutants and filter noxious gases, and the reduced energy load reduces the burning of fossil fuels, further reducing CO₂ emissions. They also reduce city noise to make the occupant space more enjoyable. Lastly, these green spaces have become an additional amenity to building owners. They can be places for building occupants to congregate and enjoy in nice weather, or places where local agriculture is produced for restaurants or local co-ops. The benefits of green roofs are numerous and wide-ranging.

Green/Living Walls

Green walls, also known as living walls or vertical gardens, work similarly to green roofs. These design interventions can be used both as interior and exterior walls. On the exterior, a building receives all the same benefits of green roofs. These include: protection of the façade from sunlight, acid rain, and ultraviolet radiation; reduced energy costs by keeping solar heat gain from entering the building; noise reduction from loud urban areas; and cleaner air.¹¹⁴

Interior living walls have the same, as well as additional benefits. Leaves of the plants actively attract particles in the air and filter them out naturally through the leaves and roots. Green walls have been proven to reduce particulates in the air by up to 20% in indoor spaces. In addition, they are continuously taking in carbon dioxide and giving off fresh oxygen, making office staff feel more awake and alert.¹¹⁵

One of the other benefits of green walls is the improvement of the general well-being of the occupants. Studies have shown that those who spend more time in green spaces are at a lower risk for depression and feel less stressed.¹¹⁶ Healthier, happier workers are also proven to be more productive and have higher levels of concentration. Interior green walls are not only good for the energy-efficiency of the building, but also for the business efficiency of the companies who occupy the space.¹¹⁷

¹¹³ Lui, 8.

¹¹⁴ <http://www.ambius.com/green-walls/index.html>, July 8, 2016.

¹¹⁵ <http://www.ambius.com/green-walls/index.html>, July 8, 2016.

¹¹⁶ <http://www.medicaldaily.com/benefits-ecotherapy-being-nature-fights-depression-improves-mental-health-and-well-being-261075>, July 8, 2016.

¹¹⁷ <http://www.medicaldaily.com/green-space-will-lower-stress-city-dwellers-reduce-heart-risks-326592>, July 8, 2016.

Interior green walls have are also able to filter greywater and contribute to reduction of storm runoff and the burden of the building on the public waste water treatment capacity. By pumping greywater up to the top of the living walls and letting the many levels of vegetation filter pathogens and particulates out of the water, a system can be developed to completely recycle water from faucets, showers and sinks within the building, acting as a natural biofilter.¹¹⁸ Unfortunately, this application has a trade-off of additional energy use due to the pumping requirements. A cost-benefit analysis on individual projects is necessary to determine whether to include this feature.

Reflective Surfaces/Cool Roofs

Another design feature that can manipulate solar energy is the use of reflective surfaces. Reflective surfaces can help either increase heat in a specific space or bounce heat away. Some of the earliest uses of reflective surfaces were in passive houses in the desert. In the winter, a reflective surface would be used to angle and multiply sunlight toward water barrels. The water would gain solar heat and act like a thermal mass for the house. At night, the water barrels would give off heat when the temperature dropped and provide passive heating.¹¹⁹

The more modern use of reflective surfaces applies mostly to roof construction. Cool roofs are made of light-colored material that reflects more light than dark-colored materials, the same concept that applies to wearing a white vs. a black shirt on a hot, sunny day. In addition to color, there are high solar-reflecting materials that can drastically reduce heat gain on a building by reflecting visible, infrared, and ultraviolet wavelengths of the sun. With traditional roofing materials, on the hottest summer days there can be a difference of more than 50°F between the temperature of the air and the roof. With reflective surfaces on roofing, the temperature difference can be as little as 5°F.¹²⁰ This cooler temperature then allows less heat to be radiated into the building and therefore less energy to be spent cooling the space. According to the U.S. Department of Energy, cool roofs can reduce annual air-conditioning energy consumption by up to 15% for a single-story building.¹²¹

There are other applications for reflective surfaces as well. Reflective paints help keep cars and even parking lots from absorbing heat. A combination of these types of surfaces is helping to combat the phenomenon of urban heat islands, where summertime weather increases temperatures in densely populated, highly-developed areas and causes more energy to be used for cooling across an entire city, putting strain on the electrical grid.¹²²

¹¹⁸ Thomas, 66.

¹¹⁹ Maclay, viii.

¹²⁰ <http://energy.gov/energysaver/cool-roofs>, July 8, 2016.

¹²¹ http://www1.eere.energy.gov/buildings/pdfs/cool_roof_fact_sheet.pdf, July 8, 2016.

¹²² <https://www.epa.gov/heat-islands>, July 14, 2016.

Car-Free Buildings¹²³

Although not directly contributing to the energy reduction of a building, the next two concepts speak toward a greater vision for our reduced dependence on non-renewable energy sources.

Car-free buildings are buildings that do not include any structured parking, surface parking or any room on-site to store vehicles. Although these do not directly reduce energy usage, they do encourage a more sustainable environment around the building itself. They encourage biking, walking, ride-sharing and the use of public transportation. These types of buildings are often tenanted by individuals and companies who have a forward-thinking mentality on sustainability, energy efficiency, and urban design. As these structures become more widespread and accepted by cities and municipalities, cities will become less congested, have cleaner air supplies, healthier residents, and an overall reduction in non-renewable energy resource use. This also has the possibility of increasing mixed-use development, creating more efficient communities and ecosystems.

Bike Storage Rooms

In the same vein as car-free buildings, bike rooms encourage a more sustainable means of transportation to and from a building. Again, this design element does not reduce energy usage in the building, but does make for a healthier tenant base and is seen as way to promote sustainable practices of those who use the space. According to Alex Wilson of Green Building Advisor, approximately 30% more energy is used getting to and from an average 20th century office building than the office building uses on an annual basis. If we are comparing that energy use to modern energy efficient buildings, the energy use is 2.4 times the energy that the building consumes.¹²⁴ With that in mind, providing tenants with the ability to alter their means of transportation is important.

Bike rooms are most useful when located on the ground floor of commercial or multifamily residential buildings, close to an entrance, so users can easily store their bikes and avoid any unnecessary hassle. Many features seen today in bike storage rooms include space-efficient bike racks, bike repair stands, public air pumps, bike washing stations, lockers, changing areas and showers.¹²⁵

¹²³ Thomas, 55.

¹²⁴ <http://www.treehugger.com/sustainable-product-design/jargon-watch-transportation-energy-intensity-of-buildings.html>, July 4, 2016.

¹²⁵ <http://www.dero.com/design-guides/bike-rooms/>, July 4, 2016.

Materials

Now that we have looked at the energy and design of a building, it is time to move onto the materials used to build the structure of the future. What follows is an explanation of some of the most important materials that are helping make the buildings we occupy as efficient as possible.

The following chart outlines the sustainable materials and associated performance. These materials are used to reduce heat gain and insulate the building, as well as make the building more sustainable overall, with recycled materials and stronger, next-generation timber instead of steel and concrete. They can reduce energy use, and help keep our water supply clean by filtering storm runoff prior to its return to ground aquifers.

Intervention	Design/Service	Performance
Window Glazing	Insulate; reduce solar heat gain	Varies by specifications and region
Triple-Paned Glass	Insulate; reduce solar heat gain	Can reduce U-values by 20% to 30% vs. double-paned windows
Smart Glass	Shade; insulate	Performance unknown
Cross-Laminated Timber (CLT)	Reduce carbon footprint	Results vary
Recycled Materials	Reduce carbon footprint	Results vary
Insulation & R-Values	Insulate	Insulation alone can reduce heating & cooling by 40%
Pervious Pavement	Runoff management	Absorbs and filters 80% to 100% of rainfall

Table 3: Material Interventions & Performance

As we have seen throughout this thesis with daylighting, building orientation, solar energy systems, etc., the glass of a building is one of the most important elements, so that is where we will start our materials analysis.

Window Glazing

Window glazing is the actual glass of a window. Window glass is one of the biggest factors in creating a sustainable, energy-efficient building. Windows can regulate how much heat is transferred through the skin of the building into the interior space. Based on the climate, alignment, and exposure of the structure, windows can be manufactured differently to suit varying needs. Glass performance is measured by metrics called U-factor and solar heat-gain coefficient.

U-factor measures the rate of heat loss experienced by the window, otherwise known as the insulating value. When there is a difference in temperature between the inside and outside of the building, the U-factor describes how much a window can maintain that difference. The lower the U-factor, the greater a window's resistance to heat loss and the better it is at insulating a structure.¹²⁶ When building a structure, a low U-factor is most important in colder climates, where heat loss can greatly affect heating energy and

¹²⁶ <http://www.efficientwindows.org/ufactor.php>, June 28, 2016.

the associated costs. Double-pane windows can achieve U-factors of 0.30 or lower, while the highest quality triple-pane windows can reach U-factors as low as 0.15.

The solar heat-gain coefficient (SHGC) quantifies how much the temperature of the interior of the building can be increased through direct or indirect solar radiation, regardless of the outside temperature. The scale for SHGC is between 0 and 1, and the lower the coefficient, the less heat that is let into the building through solar radiation.¹²⁷

With double- and triple-pane glass, argon or krypton gasses can be injected between the layers to create further levels of insulation. New technology for windows also uses energy-efficient nanogel-filled glazing gaps for windows and skylights. Manufacturers claim that it has better insulating properties than gas and that it diffuses light better and more evenly for a softer, more natural daylighting within the interior space. It is also thought to dampen sound better than traditional gas-filled gaps.¹²⁸ It is not very widely used at this point, so very little independent research exists on its energy-efficiency compared to other materials.

Triple-Paned Glass

As mentioned above, triple-paned glass is the cutting-edge of energy-efficient glazing. Triple-paned glass refers to windows with three layers of glass within the frame. Manufacturers of triple-paned windows claim that these windows can reduce U-values by 20% to 30%, meaning they are substantially more insulating than traditional double-paned glass.¹²⁹

Currently, triple-paned windows account for just 1% of all commercial windows across the U.S. There is debate over whether the additional technology is worth the cost but they are certainly more energy-efficient.¹³⁰ Glass has come a long way from the single-pane days, now with coating for low-emissivity (low-e) and insulating gasses such as argon and krypton between the layers of double- and triple-paned windows and even nano-gel filled gaps. They will continue to improve incrementally, and the next sustainable intervention is further proof of that.

Smart Glass

Smart glass is an active solar technology that is helping to eliminate the need for traditional shades and incorporating responsive shading technology right between the layers of glazing. The idea is similar to transitional lenses for glasses, the lenses that darken when exposed to sunlight, but on a much larger

¹²⁷ <http://www.efficientwindows.org/shgc.php>, June 28, 2016.

¹²⁸ <http://ameriluxinternational.com/lumira.php>, July 11, 2016.

¹²⁹ <http://www.fibertec.com/double-vs-triple-pane-windows/>, July 11, 2016.

¹³⁰ <http://www.bdenetwork.com/smart-glass-efficient-safe-robust>, July 11, 2016.

scale. This new piece of the technology is programmable for specific desired light levels and includes GPS positioning to predict the sun's angle and strength throughout the day.¹³¹

As of today, the concept is still very new and comes at a cost premium to other energy-efficient glazing options, like double- and triple-paned glass. According to one estimate, the installation costs are about 50% more than regular glass in a commercial building, however that cost is mitigated by savings in air conditioning and window treatments. There is not enough data to determine the longevity of the technology and at today's cost and efficiency would require a 10 to 15 year payback period in energy gains.¹³²

Another new and exciting technology is an in-window façade component that responds autonomously to sunlight and thermal energy, designed in Germany through a partnership between the Fraunhofer Institute of Machine Tools & Forming Technology and the Department of Textile and Surface Design at Weissensee School of Art. The wire is made of a nickel-titanium alloy that has shape-memory actuators incorporated into it. The fabric and wire design, located between the layers of glazing, responds to the sunlight and becomes rigid, spreading the fabric across the window and blocking out the sun's rays.¹³³

Constant progress has been made in terms of glass, and technology is working toward a net-zero solution. The smart glass industry's goal is to provide a façade that is a standalone net-zero element of the structure. Smart glass will be at that point when it can reach a U-factor between 0.1 and 0.2 combined with spectrally selective glass that can control light intensity, solar gain, and glare while still letting in daylight.¹³⁴ That cutting-edge technology is arriving, however, just like with other technologies discussed here, it is the cost-effectiveness of these technologies that needs to continue to advance as well.

Cross-Laminated Timber (CLT)

One material that has come full circle in the built environment is wood. Once only a technology for smaller buildings no taller than four stories, it is now seen as one of the most aesthetically pleasing and sustainable materials available.

Cross-laminated timber is a pre-fabricated type of timber that is lightweight, yet extremely strong. It has superior acoustic, fire, seismic and thermal qualities to that of traditional timber and is fast and easy to install.¹³⁵ Because CLT is manufactured for specific end-use applications, it creates almost no waste onsite.¹³⁶ CLT is made up of between 3 and 11 layers of kiln-dried lumber stacked in alternating directions,

¹³¹ <http://www.sfgate.com/business/article/Smart-glass-windows-the-cool-new-thing-4035282.php>, July 11, 2016.

¹³² <http://www.sfgate.com/business/article/Smart-glass-windows-the-cool-new-thing-4035282.php>, July 11, 2016.

¹³³ <https://www.sciencedaily.com/releases/2015/04/150409081958.htm>, July 8, 2016.

¹³⁴ <http://www.bdcnetwork.com/smart-glass-efficient-safe-robust>, July 11, 2016.

¹³⁵ <https://www.apawood.org/cross-laminated-timber>, July 11, 2016.

¹³⁶ <http://smartlam.com/about-clt/benefitsadvantages/>, July 11, 2016.

bonded and pressed.¹³⁷ Its strength comes from the alternating directions of the layers, and on a strength-to-weight ratio basis, outperforms all other building materials available, including steel and concrete.¹³⁸ Because of its strength and durability, it is becoming a viable substitute for concrete, masonry and steel in multifamily and commercial construction. Panels can be anywhere from 2 to 10 feet wide, 60 feet long, and 20 inches thick and can be used for walls, floors and roofs.¹³⁹

CLT framing can double the energy efficiency of conventional buildings due to its thermal mass characteristics. The CLT can help retain the ambient temperature of the internal environment with less energy, reducing energy expenditures for heating and cooling.¹⁴⁰ CLT also has a low carbon footprint because it stores carbon that would otherwise be released back into the atmosphere. It is often made with timber from sustainably managed forests and even from trees that have already been killed by a species of beetle, called the Mountain Pine Beetle. If these trees are not cut down and used for timber, they will decay and release carbon.¹⁴¹

CLT is the only major building material that grows naturally and is renewable. And engineered wood manufacturing requires significantly less energy to produce than steel and concrete. Today, the world's tallest CLT building is located in London and is ten stories tall, or nearly 110 feet.¹⁴² Future building plans will continue to push that limit. Architecture firm C.F. Moller has proposed a 34-story wood-framed apartment building in Stockholm, which proves that industry experts trust the strength and reliability of this product.¹⁴³ More of these buildings will be seen in the future, replacing steel and concrete for the more sustainable wood product.

Recycled Materials

Just like wood, another concept that has been around for ages is recycling. In an effort to make the smallest environmental impact possible, many designers and development teams are looking to recycled materials as a way to cut down on harmful side effects of the built environment. Many items like concrete, metal, glass, brick, and plastics can all be produced from some form of the previously used material.¹⁴⁴ Another popular trend is recycling the materials that were found on site when working with ground up development, like timber for instance.¹⁴⁵

¹³⁷ http://en.openei.org/wiki/Cross-Laminated_Timber_Panels, July 11, 2016.

¹³⁸ <http://smartlam.com/about-clt/benefitsadvantages/>, July 11, 2016.

¹³⁹ <https://www.apawood.org/cross-laminated-timber>, July 11, 2016.

¹⁴⁰ http://en.openei.org/wiki/Cross-Laminated_Timber_Panels, July 11, 2016.

¹⁴¹ <http://www.bdcnetwork.com/5-myths-about-cross-laminated-timber>, July 11, 2016.

¹⁴² <https://www.ribaj.com/products/europe-s-tallest-cross-laminated-timber-building-tops-out-in-london-s-hackney>, July 11, 2016.

¹⁴³ <http://www.cfmoller.com/p/HSB-2023-Vasterbroplan-i3048.html>, July 15, 2016.

¹⁴⁴ <http://www.usgbc.org/Docs/Archive/General/Docs5497.pdf>, July 11, 2016.

¹⁴⁵ <http://www.archdaily.com/155549/recyclingbuilding-materials>, July 11, 2016.

Other less mainstream recycled materials are out there as well. Plastic pellets from recycled plastic can be used as part of asphalt laying. Newspaper can be recycled and pressed into timber, plastic bags can be gathered and compressed into blocks that can be built into separating walls, although their lightweight properties exclude them from being load-bearing.¹⁴⁶ Other things that can be recycled from the built environment include: acoustical ceiling tiles, asphalt, asphalt shingles, cardboard, carpet and carpet padding, concrete, drywall, fluorescent lights, metals, paint, window glass, and wood.¹⁴⁷

It is important to keep in mind that there are alternatives to brand new materials, and the more developers create demand for recycled product, the more people will look into the possibility of supplying them. These materials can make for a unique building with a better story than a traditional glass box.

Insulation and R-Values

Everyone has heard of insulation and probably seen rolls of it between studs in residential construction, but good insulation can be overlooked for its importance in the overall strategy of energy-efficiency. Insulation is a technology that can prevent heat transfer through walls, ceilings, and floors, as well as lower energy use within a building. The higher the R-value of insulation, the better it is at preventing the transfer of heat either in or out of the structure. According to experts, walls should be at least R-19 and ceilings should be between R-30 and R-40 or higher.¹⁴⁸

Insulation comes in 4 different forms: rolls and batts, loose-fill insulation, rigid foam insulation, and foam-in-place insulation. Many typical older structures use rolls and batts that fit traditional stud widths. Older homes may have lower R-value insulation, as typical older stud widths only fit R-13 to R-15 batts. Rigid foam insulation is the most efficient and can range from R-4 to R-6.5 for each inch of thickness, however it can be harder to install with certain envelope systems. Wood frame construction is the most prone to heat loss due to a lack of insulation.¹⁴⁹

Combined with roof radiant barriers, reflective insulation, and foundation insulation, homes can reduce energy usage and reduce draftiness within the home. Insulation alone can decrease the cost of heating and cooling by over 40%, and it is an easy, low-tech solution that pays for itself in 5 to 6 years.¹⁵⁰

Pervious Pavement

Pervious pavement is a porous substance used for paving parking lots and roads. It allows for storm water to penetrate normally impervious surfaces instead of overburdening sewer systems. The pervious

¹⁴⁶ <http://www.citymetric.com/skylines/9-building-materials-made-entirely-waste-products-932>, July 11, 2016.

¹⁴⁷ <http://www.usgbc.org/Docs/Archive/General/Docs5497.pdf>, July 11, 2016.

¹⁴⁸ <http://www.hgtv.com/remodel/mechanical-systems/why-r-values-matter-in-energy-efficiency>, July 6, 2016.

¹⁴⁹ <http://energy.gov/energysaver/types-insulation>, July 15, 2016.

¹⁵⁰ <http://www.greenhomegnome.com/energy-loss-homes-insulation/>, July 15, 2016.

pavement captures the water and allows it to slowly seep into the ground, reintroducing it to the groundwater. It is one of the recommended best practices by the U.S. Environmental Protection Agency. It allows for more efficient use of land, especially in densely populated areas, by eliminating or reducing the need for retention ponds, rain gardens, Bioswales, and other runoff-mitigating elements.¹⁵¹

The pervious formula is made without the use of sand so there exists anywhere from 15% to 25% voided area for water to penetrate. It allows between three and eight gallons to penetrate the surface of the pavement per minute in a square foot of space. According to the EPA, this type of pavement can absorb between 80% and 100% of rainfall and filter out particulates and pollutants before returning the water to the ground aquifers.¹⁵²

Water & Waste

Our last material intervention above, pervious pavement, makes the perfect segue into the water and waste intervention list. Energy is clearly an important piece of sustainability, but water is just as important as we head into the future. Humans are approximately 70% water¹⁵³ and as the population continues to grow, with estimates of a world population increasing from 7.4 billion people today¹⁵⁴ to 9.7 billion by 2050,¹⁵⁵ it stands to reason that water will become more and more valuable. While the world is approximately 70% water, less than 3% is fresh water. And of that 3%, much of it is inaccessible, tied up in ice caps and glaciers. Only about 0.3% of our fresh water is found in lakes, rivers, and swamps and is available for human consumption.¹⁵⁶ It is for these reasons that conservation of water is so important. In addition to the growing scarcity of water, the built environment uses large amounts of energy to move water and waste around our cities. It is estimated that the transportation of water and waste accounts for 45 million tons of greenhouse gas emissions on an annual basis.¹⁵⁷ Treating water on-site instead of moving it through public systems could greatly reduce that pollution and wasted energy.

As we mentioned in the introduction, the built environment is responsible for 25% of global water consumption. As important as water is as a resource, developers and building owners can use the following interventions to reduce water usage, reuse water where possible, and treat water on-site to mitigate the strain on public water treatment systems.

¹⁵¹ <http://www.perviouspavement.org/>, July 11, 2016.

¹⁵² <https://www.epa.gov/soakuptherain/permeable-pavement>, July 11, 2016.

¹⁵³ <http://www.nasa.gov/vision/earth/everydaylife/jamestown-water-fs.html>, July 15, 2016.

¹⁵⁴ <http://www.worldometers.info/world-population/>, July 15, 2016.

¹⁵⁵ <http://www.un.org/en/development/desa/news/population/2015-report.html>, July 15, 2016.

¹⁵⁶ <http://nationalgeographic.org/media/earths-fresh-water/>, July 15, 2016.

¹⁵⁷ <https://www.greenbiz.com/blog/2014/02/12/net-positive-add-water-buildings>, July 21, 2016.

Below is a list of technology and strategy solutions for reducing a building’s impact on the water supply. Because of precipitation differences, many of these systems have varying results. The most commonly used intervention, low-flow fixtures, can reduce water use by more than 3 trillion gallons on an annual basis.

Intervention	Design/Service	Performance
Rainwater Collection	Reduce water use; Runoff mgmt.	Offset building water needs by up to 100%
Bioswales	Runoff management	Filter particulates and chemicals out of storm runoff
Rain Gardens	Runoff management	Filter particulates and chemicals out of storm runoff
Lagoons	Waste treatment	Treat wastewater using natural processes
Greywater/Wastewater Treatment	Water /waste treatment	Results vary.
Low-Flow Fixtures	Reduce water use	Reduce annual water use by 3 trillion gallons nationwide
Composting Toilets	Reduce water use	Use 0 gallons of water annually
Biodigesters & Biogas	Water /waste treatment	Performance Unknown
Pneumatic Waste System	Waste management	Performance Unknown

Table 4: Water & Waste Interventions & Performance

Rainwater Collection¹⁵⁸

Rainwater harvesting is a practical way to reduce water usage from municipal water systems. Rainwater is used mostly for flushing toilets and irrigation, although can be filtered and treated properly for use in showers, sinks, and drinking fountains. The system is fairly simple and consists of a catchment area (typically the roof), the gutters and piping system, and the storage tank to which the pipes lead. More advanced systems then have pumps that can pull water to where it is used, like bathrooms, green roofs, and on site agriculture. Systems used to filter it are described in the greywater treatment section below.

Bioswales¹⁵⁹

Not all rainwater can hit the roof of a structure, so other means are necessary for managing the runoff. Bioswales are meant to manage runoff from large impervious areas and are often seen in medians between streets or next to large commercial parking lots. They are meant to handle large amounts of storm water, so they are designed as deep ravines and usually have specially engineered soils. They are similar to rain gardens but are much larger and often linear systems, especially along roadways. They use dense vegetation to help filter and purify water of chemicals and particulates before it is returned to the groundwater supply. They are useful from minimizing the amount of storm water directed to drains and into the wastewater treatment system. The most effective systems contain soil that can slow down, filter, and hold water, giving the plants more time to absorb and clean the runoff.

¹⁵⁸ <http://sustainabilityworkshop.autodesk.com/buildings/rainwater-harvesting>, July 9, 2016.

¹⁵⁹ <https://www.soils.org/discover-soils/soils-in-the-city/green-infrastructure/important-terms/rain-gardens-bioswales>, July 11, 2016.

Rain Gardens¹⁶⁰

Rain gardens are simple landscaping elements that help to reduce storm water runoff directly into the municipal system. They typically collect water runoff from sidewalks, driveways, and roof gutters and are more common around residential buildings. Storm water collects dirt, rocks, sand, and other particles that then have to be removed by the wastewater treatment plants, which takes additional energy and resources. Rain gardens can help mitigate this problem by filtering the water and returning it to the ground. Rain gardens are built with a slight depression to help collect water. They are inhabited by vegetation that can handle wide ranges of moisture saturation and survive in temporary flood and/or dry conditions.

Lagoons

Lagoons are a low-cost, energy-efficient way of treating wastewater. They rarely require pumps or motors, instead using gravity to create water flow. They include one or more water basins to receive, hold, and treat the wastewater through a combination of physical, biological, and chemical processes. Much of the treatment occurs naturally, but aeration can help increase the amount of oxygen the water receives and speed up the treatment. These systems can be used to serve individual buildings, however they can take up large amounts of space, so they are difficult to use in more urban areas.¹⁶¹

Lagoons use aerobic bacteria and algae to treat the water and remove disease-causing pathogens. The system stabilizes organic material through a process involving sunlight, water, nutrients, algae, atmospheric oxygen, and bacteria. The organic matter is broken down by the aerobic bacteria and oxygen. This process releases carbon dioxide as a byproduct, which the algae then uses to produce simple sugars through photosynthesis. The byproduct of this natural process is oxygen, which is used by the bacteria to break down more organic material, creating a self-sustaining cycle, all played out using natural processes.¹⁶²

These lagoons are typically the second step in wastewater treatment processes, at the building-level or the larger-scale community wastewater treatment plant level, after some sort of primary filtration is used to reduce the level of solid material. Although they require less energy than other types of water treatment, the water after this stage is only good for irrigation purposes. There is further treatment, or polishing, needed before this water is fully treated and ready to be put back into the water supply.¹⁶³

¹⁶⁰ <http://www.montgomerycountymd.gov/DEP/water/rain-garden.html>, July 11, 2016.

¹⁶¹ http://www.nesc.wvu.edu/pdf/WW/publications/pipline/PL_SP97.pdf, July 11, 2016.

¹⁶² <http://www.waterworld.com/articles/print/volume-27/issue-10/editorial-features/introduction-to-wastewater-treatment-ponds.html>, July 11, 2016.

¹⁶³ http://www.nesc.wvu.edu/pdf/WW/publications/pipline/PL_SP97.pdf, July 11, 2016.

Greywater/Wastewater Treatment Systems

Greywater is defined as rainwater as well as water that has been used in sinks, showers, tubs and washing machines. Wastewater is all greywater plus the water and human waste that is flushed down toilets. The ability to purify and reuse all the water that a building consumes has many benefits, including reduced strain on municipal storm and wastewater systems, and reduced water use on site, which reduces water bills.

Greywater treatment and reuse is much easier than wastewater reuse. One building that has made use of this technique is the Bullitt Center. Through charcoal filtration, ultraviolet radiation, and the addition of chlorine, the system in the Bullitt Center is able to recycle rainwater, shower water, and water from sinks into potable water to be used over again.¹⁶⁴ There are also companies working on all-in-one technology that can take greywater or wastewater straight to drinking water. One of those technologies is called CleanBlue Water, however this technology is not widely dispersed and still has regulatory hurdles in many places.¹⁶⁵

There are a number of different systems at the building-level that can perform wastewater treatment functions. The Eco Machine is a nature-influenced technology designed by John Todd, a pioneer in the field of ecological design. The system is implemented at the Omega Center for Sustainable Living. It cleans the water by mimicking processes of nature. The water from an entire building is purified by microscopic algae, fungi, bacteria, plants, and snails, and the whole process uses zero chemicals. The water is returned to the natural aquifer deep below the building's parking lot. The system has seven different steps: solid settlement tanks, equalization tanks, anoxic tanks, constructed wetlands, aerated lagoons, recirculated sand filter, and dispersal fields. The system can process 52,000 gallons of water daily.¹⁶⁶ However this system requires large plots of land, so is not suitable for most urban sites.

Another system is called the Living Machine. The Tidal Flow Wetland Living Machine combines technology and engineering with beneficial bacteria to efficiently treat wastewater on site. It is set up as a series of wetland basins filled with special gravel that promotes the development of small ecosystems. These small ecosystems are incorporated into a building's outdoor landscaping or can be housed within the building. The water moves through the system and the plant life efficiently removes particles, nutrients and solids from the water. A final stage involves filtration and disinfection, leaving the water crystal clear and ready for reuse. Online sensors monitor the water quality to ensure the output water is safe. The system

¹⁶⁴ Thomas, 66-72.

¹⁶⁵ <https://www.bluewater-technologies.com/>, July 9, 2016.

¹⁶⁶ <https://www.eomega.org/omega-in-action/key-initiatives/omega-center-for-sustainable-living/eco-machine%E2%84%A2>, July 9, 2016.

can recycle thousands of gallons of water a day and all building occupants or neighbors see is the vibrant plant life on the surface.¹⁶⁷

These systems are still somewhat rare for a number of reasons. Public perception, sophistication, building codes, public health laws, and cost all play a role in slowing the adoption of this intervention.

Low-Flow Fixtures¹⁶⁸

Although this is one of the most well-known interventions, it is still worth mentioning. One of the first ways that water usage can be reduced is by the installation of low-flow faucets, toilets and showerheads. This technology has been around for some time and is now standard practice in new construction. These fixtures use high pressure to offset the lower volume of water. Although these are now commonplace in most new buildings, in older buildings replacing outdated, traditional fixtures will go a long way to reducing water waste.

Standard toilets use about 3.5 gallons per flush, whereas low-flow toilets use somewhere around 1.3 gallons, a mere 37%. For showerheads, older models used about 4 gallons per minute while new low-flow models use around 2.5 gallons. And for sinks, low-flow models use no more than 1.5 gallons per minute compared to traditional models using 2.2 gallons. According to the EPA, if every household in the U.S. switched from traditional fixtures to low-flow fixtures, it would save 3 trillion gallons of water, or what amounts to \$18 billion dollars on the collective water bill.¹⁶⁹ The energy used to treat and transport that water only adds to the inefficiency of these older fixtures.

Composting Toilets

Composting toilets are a way to process all toilet water and waste onsite and avoid using large amounts of water in the process. Composting toilets can be even waterless, but some use a small amount of water or foam for flushing. They can either be self-contained units or be linked to a central system.

In large, commercial buildings, a central system is preferable. The system is often designed so the toilet's pipes are perfectly vertical and feed directly into the treatment container, usually located in the basement of the building. The waste travels to a central tank, often with multiple chambers. The first chamber is for new waste and the other contains more mature composted waste that can be removed separately for use as fertilizer, etc. In the first chamber, waste is mixed with wood chips, saw dust, or other dry, carbon-based material to absorb moisture and to achieve the correct carbon-to-nitrogen ratio. Over time, the waste breaks down and decreases in volume. The fully composted byproduct can be used as

¹⁶⁷ <http://www.livingmachines.com/About-Living-Machine/Tidal-Flow-Wetland-Living-Machine-System.aspx>, July 9, 2016.

¹⁶⁸ <http://challengeforsustainability.org/toolkit/water-efficiency/office-fixtures/>, July 11, 2016.

¹⁶⁹ <http://www.thegreenspotlight.com/2010/08/high-efficiency-water-saving-plumbing-fixtures/>, July 15, 2016.

fertilizer or combined with an outdoor compost pile. For many central systems, it will likely be two years before emptying is necessary, and after that it only needs annual emptying.¹⁷⁰ Additional features are useful in commercial systems as tenants may be wary of a composting system. A design feature added at the Bullitt Center was the use of negative air pressure in the system that always pulls air down through the toilets on each floor, eliminating any odor that might dismay tenants.¹⁷¹

The advantages of composting toilets are numerous. First off, a quarter of the water typically used in a building is flushed down toilets. Composting toilets all but eliminate this water use, conserving water on a large scale. Also, public wastewater treatment systems and sewer needs are diminished or eliminated, depending on what other systems are included in the building. Lastly, the creation of nutrient-rich fertilizer could be used as a secondary source of income, depending on the local demand.

As with greywater treatment, composting toilets are a new idea that takes some time to get used to for building occupants. The hope is that as they become more widespread, they are more accepted and can be utilized across more of the built environment.

Biodigesters and Biogas¹⁷²

The tanks that collect and process the waste from composting toilets are sometimes called biodigesters, and they can have an additional role in the sustainability of the building. A biodigester is an airtight chamber where bacteria break down organic waste matter in the absence of oxygen, a process called anaerobic digestion. Organic waste can include manure, biosolids, food waste, and organic wastewater streams. The process of breaking down organic matter creates a biogas, a combination of methane and carbon dioxide, and fertilizer. Benefits of biodigesters include reduced greenhouse gas emissions, renewable energy production, mitigation of water pollution, and possible financial savings or secondary revenue streams for a building, from fertilizer, renewable energy credits, carbon offsets, and biogas.

Anaerobic digestion is the same process that goes on in most wastewater treatment facilities, but without the added benefit of capturing the biogas. Anaerobic digester systems are already common in public and private infrastructure, including private and municipal wastewater treatment facilities, however very few capture the byproduct biogas. Biogas has the ability to generate electricity and mechanical energy, or the potential to fuel steam production, space and water heating. However, it was estimated in 2009 that only 2% of wastewater treatment with biodigesters use the biogas to generate energy.

Biogas and biodigesters can also be included with combined heat and power systems (CHP) to generate heat and electricity at a building. In addition, biogas can be converted to compressed natural gas

¹⁷⁰ <https://www.go-gba.org/resources/green-building-methods/composting-toilets/>, July 11, 2016.

¹⁷¹ Thomas, 74.

¹⁷² https://www.americanbiogascouncil.org/pdf/biogas_primer_EPA.pdf, July 4, 2016.

and used for a variety of fuel applications, including vehicle fueling. By putting a biodigester system in the building, owners can avoid putting wastewater and other waste materials into the municipal system and take that burden off public systems. In addition, the materials can be used to generate heat and electricity sustainably, cut down on energy bills and lower emissions, while creating an additional source of income for the byproducts.

Pneumatic Waste System¹⁷³

Pneumatic waste systems are gaining popularity as society starts to realize how much of an impact waste has on our environment. Pneumatic waste systems consist of underground pipe networks that can transport waste directly from buildings or neighborhood collection points to a waste station. The underground pipes are typically about 20 inches in diameter and made of steel. The waste stations can be as far as 1.25 miles away from where the waste is being put into the system. The system uses vacuum suction and pressure to pull waste from waste inlets to the main station. Blockages can be removed by over-pressurizing the system. The system of pipes can be set up in two ways: as a tree and branch system, or a ring system. The ring system is more economical and allows for both a push and pull force to be applied to the pipes to move waste along, whereas the branch system only allows for a pulling force to collect the garbage.

Instead of garbage trucks and receptacles at the street, inhabitants of a city can bring garbage to a waste inlet at any time, set up to easily accommodate the population without long travel required. This system reduces payroll costs for the city, reduces fuel costs and emissions from garbage trucks, and reduces sanitation issues from garbage left on the street for pickup. A tertiary benefit of these systems is the increase in recycling in places where the system allows for multiple input channels for waste and recycling. Because there is no special bag, bin or process that complicates recycling, residents are more likely to participate in the separation of the two kinds of waste at the point of collection.

While the initial investment is quite high, long-term savings do exist for the system. Building the network of pipes underneath an existing city can prove to be a challenge, but the system pays for itself over time, an estimated payback period of 10 to 12 years. While this may seem like a long payback period, one company who manufactures the technology estimated that the system will last upwards of 60 years, so in the long-run it is a feasible investment.

The system is growing in popularity. Helsinki, Finland and Montreal, Canada plan to incorporate it into new urban development projects,¹⁷⁴ and South Korea's Songdo International Business District is

¹⁷³ <https://waste-management-world.com/a/the-future-of-waste-collection-underground-automated-waste-conveying-systems>, July 11, 2016.

¹⁷⁴ <http://gizmodo.com/the-not-so-crazy-plan-to-solve-nycs-trash-woes-with-pn-1342822457>, July 11, 2016.

equipped with a system already.¹⁷⁵ Helsinki will include about 350 collection points in their newest residential district, Jatkasaari, with a daily capacity of 22,000 kg (48,500 lbs.).

Although retrofitting of these systems is a challenge, new development initiatives are encouraged to build the infrastructure. The combination of energy savings, safety, and health benefits combine to prove that this system is something that belongs in the cities of the future.

¹⁷⁵ <http://www.usgbc.org/articles/koreas-songdo-international-business-district>, July 11, 2016.

Part III: Sustainable Building Case Studies

Below are two buildings that have gone above and beyond to achieve the highest sustainable certifications in two different programs, the Living Building Challenge and LEED. The following case studies detail their approaches to sustainability and energy- and water-efficiency. Only one of these buildings has been able to achieve net-zero status in energy and water. The other is anticipated to be certified at the LEED Platinum level, but originally had hopes of net-zero status before discovering how difficult that achievement can be.

The first building, the Bullitt Center, was chosen because it is the first and largest multi-story office building in the world to achieve net-zero status. In its first year, it was actually net-positive in energy at an 85% occupancy rate. The second building, the Darla Moore School of Business, worked in partnership with the Department of Energy under their net-zero program. They reached a net-zero ready status and have applied for LEED Platinum status, but have yet to add any renewable energy sources to the site. The buildings show vast differences in energy consumption even though they are striving for the same goal. One as an office building had a target EUI of 16, while the other as an institutional academic building had a target EUI of 68. This disparity shows the large spectrum of energy needs in commercial buildings. It also suggests how difficult it is to reach net-zero status. As of 2015, there were only 39 buildings in the entire United States that had reached this accomplishment.¹⁷⁶

Case Study #1: The Bullitt Center, Seattle, WA

The Bullitt Center, located in the Capitol Hill neighborhood of Seattle, is a 52,000 square-foot, 6-story office building that is one of the most sustainable commercial buildings in the world.¹⁷⁷ It was designed to Living Building Challenge (LBC) standards, and was the first multi-story office building to ever receive the certification.¹⁷⁸

The Bullitt Center is named after the Bullitt Foundation, a foundation with a rich philanthropic history focused on environmental improvement and urban ecology. They are heavily involved in land conservation efforts and protection of the environment, focusing on Washington State. It was in the early 2000's when they were looking for new office space that the idea to build a model for sustainability began to take hold. During their search for office space, they found nothing that matched the mission of the firm in terms of sustainability, so they decided to build it instead. Their goal was to build something that aligned with their mission as a foundation, and the idea for the Bullitt Center was born.

¹⁷⁶ <https://newbuildings.org/wp-content/uploads/2015/11/2015ZNEbuildingsListI.pdf>, July 19, 2016.

¹⁷⁷ <http://www.bullittcenter.org/>, June 23, 2016.

¹⁷⁸ Thomas, 172.

The president and CEO of the Bullitt Foundation, Denis Hayes, joined the company in 1992. He has a rich history of involvement in environmental causes and helped coordinate the first Earth Day as a graduate student at the age of 25. He was the driving force behind the project and stated to his design team that the goal of this building, beyond meeting the LBC certification, was to develop a building that was not just net-zero in terms of energy, but net-positive.¹⁷⁹

The goal of the Foundation was to create something that would serve as a green demonstration piece for the Pacific Northwest region, as an educational tool for others who wanted to pursue such levels of sustainability. They also were dismayed at the conventional wisdom of designing buildings with a lifespan of 50 or 75 years. For the amount of energy and environmental impact it takes to build a new project, they knew that the Bullitt Center had to be built to last. That is why the structure was designed to have a lifespan of 250 years. The structural foundation elements are engineered for centuries, while the skin and solar technologies are designed to be shed every 25 to 50 years and updated with the newest technologies.¹⁸⁰

The team was brought together beginning with the developer. Point 32, a sustainability-oriented development firm was selected by Mr. Hayes to lead the project. Together, the Bullitt Foundation and Point 32 tracked down a site in the Capital Hill neighborhood that had the potential to bring this project to life. That site was purchased in April 2008. From there, Robert Peña was brought in, a faculty member from the Architecture Department at University of Washington. Peña, along with a number of his graduate students, the owner, and the developer held weekly meetings to assess strategies and discuss other sustainable building projects and topics.

Next, an exhaustive search for an architecture firm was conducted, focusing on firms that had green experience, great design skills, and were based in the Pacific Northwest with familiarity of the region. Eventually, the Miller Hull Partnership was selected because of their experience with sustainable projects and their leadership in passive solar design. Mr. Hayes also loved their use of locally sourced timber in many of their projects and thought that aesthetic would fit nicely into the project they were striving to create.

Because of a great working relationship with Miller Hull, PAE was brought on board as the engineering firm for the project. They had a long history of design-build experience and were also involved in a number of cutting edge projects.

Lastly, the general contractors were brought on board, a firm called Schuchart. They had deep Seattle roots, a family-run operational framework, and a previous working relationship with Point 32. All of these pieces were assembled before they had their first design meeting. It was this cohesive team that

¹⁷⁹ Thomas, 31.

¹⁸⁰ Thomas, 34-35.

would have a hand in the development of this building from day one, and it is that process that allowed the project to be so successful.¹⁸¹

The project made good use of a substantial pre-design phase, where building size and massing, architectural and MEP systems, and renewable energy production potential were proven, prior to the start of schematic design.¹⁸² Simulation software played a major role in determining the eventual success of the project before a shovel was ever put in the dirt. The project used Array for its design software and eQuest for its energy simulations.¹⁸³ Every design decision was driven by the net-zero energy targets and the requirements of the Living Building Challenge. Various geometric layouts were tested, carefully analyzing daylighting, solar exposure, energy needs, and usable square footage. It was the daylighting of the building that drove massing, building alignment, and the choices behind the curtain wall and glazing for the building.¹⁸⁴

One of the biggest challenges of the project was the regulatory process. The technology existed to achieve everything that the team had set out to do, but building, health, and public safety codes were an impediment to the process. Many of the sustainable solutions that were proposed were illegal under the current legislation of the city, state, and even country. It took a very close working relationship with many agencies to assure that this project was able to get off the ground. Seattle developed a Living Building Pilot Program¹⁸⁵ that allowed for rules and regulations to be temporarily altered for this building and nine other future buildings as a way to vet the performance of this type of development. The development team had to work with city, county, and state officials, as well as the regional EPA, the national EPA water chief, and the head of the U.S. EPA before they could complete the project as desired.

Coordinating construction proved to be another challenge. The elements used in the construction of the building were all commercially available at the time, but no project had ever used this many different interventions together in one building. It took great communication among the development team to integrate the numerous systems in an efficient manner, which is part of why the entire team was brought in at the very beginning of the process. It was through these open lines of communication that changes were able to be made while still keeping everything running on schedule. For example, the location and depth of the geothermal heat wells were adjusted during the process to take up less room on the site, so that other activities could begin at the same time, saving weeks on the timeline of the project.¹⁸⁶

¹⁸¹ Thomas, 26-29.

¹⁸² https://www.wbdg.org/references/cs_bullittcenter.php, July 24, 2016.

¹⁸³ https://www.wbdg.org/references/cs_bullittcenter.php, July 24, 2016.

¹⁸⁴ <http://www.aiatopten.org/node/427>, July 27, 2016.

¹⁸⁵ Thomas, 41.

¹⁸⁶ <http://casestudies.uli.org/wp-content/uploads/sites/98/2015/02/TheBullittCenter1.pdf>, July 24, 2016.

Another example of the intricacies of the design and planning of the building can be seen in the façade and solar array of the building. The development team designed the building so that the curtain wall and solar panels were the last layer to be put onto the building. When those elements are due for replacement in exchange for updated technology, they are easily removable. The solar array is not part of the actual roof enclosure, so replacing it does not compromise the thermal envelope of the building. And the curtain wall and window system is designed so that it can easily be unbolted and switched out without disturbing any other elements or systems of the building.¹⁸⁷

The total project costs were \$32.5 million, \$18.2 million of which went to hard costs.¹⁸⁸ That \$18.2 million investment is approximately 25% more than what it would cost to build a traditional building on the same site.¹⁸⁹ And soft costs were significantly higher because of the amount of research that was required by the design team, as well as the regulatory hurdles that had to be overcome, and the overall length of the project.

The development of this building also challenges the modern financing models of today's buildings. Frequently, the external costs of buildings are passed on to the public without any responsibility on the part of the owners. The Bullitt Center was able to internalize those externalities, including pollution, carbon emissions, and health costs of occupants, without any financial reward. Instead, the building forwent traditional value and instead sought to internalize these externalities which usually fall on the shoulders of the municipality and the building occupants.¹⁹⁰ It is the hope of the design team that because of the work put into this project, that subsequent projects would run more smoothly and that many of these costs would be one-time expenditures. The Bullitt Foundation was more than happy to take on that financial burden, being that it fit so closely with their mission to develop a sustainable model for the built environment worth replicating.

A report by Ecotrust found \$18.5 million in hidden value over the life of the building from just six of its green features. This is the first time that ecosystem service value, or the value of the benefits to the environment, have been calculated for a building. Unfortunately, current regulatory and financial systems often do not fully account for these value components. A quote from the Denis Hayes sums it up best: "Society does not acknowledge the benefits that deep green buildings provide to the general public. By ignoring the benefits such investments provide to society at large, we penalize the best buildings and reward the worst." The value was attributed to the following six features: Site transportation (\$2.93 million), rainwater capture & reuse (\$910,000), composting toilets (\$680,000), energy efficiency (\$10.27 million), solar array (\$3.28 million), and FSC wood (\$370,000). The report also mentions that the value of some

¹⁸⁷ https://www.wbdg.org/references/cs_bullittcenter.php, July 24, 2016.

¹⁸⁸ <http://casestudies.uli.org/wp-content/uploads/sites/98/2015/02/TheBullittCenter1.pdf>, July 24, 2016.

¹⁸⁹ Thomas, 42.

¹⁹⁰ https://www.wbdg.org/references/cs_bullittcenter.php, July 24, 2016.

components is immeasurable, but still have large extrinsic values to the project. For instance, the mitigation of stormwater runoff from the site has no calculated value, but the city of Seattle just spent \$1 billion to address stormwater issues it currently faces. Seeing as the Bullitt Center has zero annual stormwater runoff, there is clearly value in such an intervention.¹⁹¹

The timeline for the development was also extended due to the complexity of the design and the rigorous regulatory process. As stated previously the land for the project was purchased in April 2008. It was not until June 2009 that the project team was fully assembled and the first design meeting occurred involving everyone from the owner down to the general contractor.¹⁹² More than two years later, the project broke ground on August 29, 2011 and was delivered on Earth Day 2013, in April. The project began tracking performance data in January of 2014 when occupancy had reached a critical mass. And in April 2015, the building earned its certification as a Living Building.¹⁹³

Below is a table outlining the various sustainable interventions, which are then further explained in detail. The combination of these interventions utilized in the development of Bullitt Center allowed the project to meet its goals of net-zero energy and water.

Energy	Design	Materials	Waste & Water
Photovoltaic Solar Panels	Green Roof	Window Glazing	Rainwater Capture
Energy-Efficient Equipment	Daylighting/Natural Light Elements	Triple-Paned Windows	Greywater Treatment System
Occupant Behavior (Lease Agreements)	Upturned Beam Design	Toxin-Free Materials	Composting Toilets
Geothermal Heat Pumps	Irresistible Staircase	FSC Timber	Bioswale
Radiant Floor System	Natural Ventilation	Recycled Materials	Pervious Pavement
Energy-Efficient Smart Elevator	Bike Storage Room		
	Car Free Building		

Table 5: Bullitt Center Sustainable Interventions

¹⁹¹ <http://www.bullittcenter.org/2014/09/15/report-finds-18-5-million-in-hidden-value-at-bullitt-center/>, June 26, 2016.

¹⁹² Thomas, 37.

¹⁹³ Thomas, 172.



Exhibit 1: Bullitt Center Exterior Façade & Underside of PV Solar Array



Exhibit 2: Bullitt Center Interior Work Space and Conference Room

Photovoltaic (PV) Solar Panels¹⁹⁴

The photovoltaic solar array at the building covers an area of 14,303 square feet on the roof and is made up of 575 panels that have a capacity of 425 watts per panel. As you can see in images of the building, the array does not just cover the footprint of the building, but the footprint of the entire site, creating large overhangs on all sides of the building. The site is zoned for a maximum height of 65 feet, while the area immediately south of the site has limits of just 35 feet, ensuring that the solar panels will not be obstructed from the sunlight by future development.¹⁹⁵

At the time, the panels used were the most efficient commercially available units in production, aside from the massive industrial applications used by the U.S. space program. It is estimated that the array produces 240,000 kilowatt hours annually. Matching this output to the energy consumption of the building proved to be one of the hardest parts of the whole process. However, in its first year of occupancy, the solar array produced 243,000 kilowatt hours of energy and the building used only 153,000 kilowatt hours, producing 60% more energy than it consumed.¹⁹⁶

Energy-Efficient Equipment & Occupant Behavior¹⁹⁷

Tenants were required to sign low-use commitments and stick to strict energy caps if they wanted to rent space in the Bullitt Center. To do this, one of the first tenants, PAE (also the engineering firm on the project), looked at matching the machinery they were using, like computers and printers, to the actual jobs they were being used to do. Many times machines have much more power than they need for what tasks are actually being performed. By optimizing machinery, occupant energy loads could be significantly reduced. PAE was able to reduce their energy consumption per employee by 82%. Work stations went from running about 260 watts down to around 50 watts. Computers, printers, monitors, etc., were all purchased with the end goal of energy conservation in mind.

Geothermal Heat Pumps¹⁹⁸

The property contains 26 bore holes that extend 400 feet below the earth's surface. Within those holes are ground-source heat loops that extract heat from the ground and deliver it to the heat pumps, which in turn increase the temperature through compressors and small amounts of electricity, then transfer the heat to the building's heating system. In the summer, the system can be run in reverse to extract the cooler temperatures from the earth compared to the outside air.

¹⁹⁴ Thomas, 98.

¹⁹⁵ <http://casestudies.uli.org/wp-content/uploads/sites/98/2015/02/TheBullittCenter1.pdf>, July 24, 2016.

¹⁹⁶ <http://casestudies.uli.org/bullitt-center/>, July 24, 2016.

¹⁹⁷ Thomas, 95.

¹⁹⁸ Thomas, 102-103.

Radiant Floor System¹⁹⁹

The geothermal exchange system pumps heated or cooled water through the pipes laid within the concrete floor slabs of the building. The radiant floor slabs affect the temperature of both the air and the furniture throughout the building. This regulation program allows for less energy to be used than blowing hot or cold air over the tenants and the space, and is easier to adapt to for the human body. Instead of dressing for the winter and then getting into the office and sweating from the heated building, occupants can dress for the outside weather and then have less of a startling temperature change when they arrive at the building. The building more closely mirrors the external seasonal temperatures rather than creating temperature extremes at either end of the spectrum.

Energy-Efficient Smart Elevator²⁰⁰

The elevator on-site converts the kinetic energy captured during the descent into electricity that helps power the elevator during ascension. It saves roughly 60% of the electricity used by a standard elevator. This is the same Gen2 Otis elevator discussed in the Energy section of Part II.

Daylighting & Uprturned Beam Design²⁰¹

The daylighting solution that was utilized included an unconventional way of framing the Bullitt Center structure. The building was framed with the upturned beam design discussed earlier, which freed up an additional eight inches of glazing through which daylight could penetrate into the structure. This approach was coupled with a floor-to-floor height of 13'10", allowing for sunlight to extend an additional three to four feet into the interior space. This led to 82% of the total floor area of the building being lit by natural daylight, and 90% of the light on floors three through six coming from natural sources during daytime hours.²⁰² In addition, gaps were left in the PV array on the roof that allowed skylights to be installed and natural light to penetrate down into the sixth floor office space. Because of the irregular shape of the building as opposed to the perfect rectangle of PV panels, this did not waste any opportunity for additional solar energy capture.

¹⁹⁹ Thomas, 116.

²⁰⁰ Thomas, 114.

²⁰¹ Thomas, 91.

²⁰² <http://casestudies.uli.org/wp-content/uploads/sites/98/2015/02/TheBullittCenter1.pdf>, July 24, 2016.

Irresistible Staircase²⁰³

As mentioned earlier, the staircase at the Bullitt Center coined the term ‘Irresistible Staircase’. The goal was to make the stairs so inviting that no one who was physically able would choose the elevator. The staircase exists within a glass enclosure and is only conditioned to prevent freezing. Because people would be walking up as many as six flights of stairs, designers did not see a reason for it to be heated. At the top of the staircase are automatic windows that open when the temperature gets too warm. The hot air goes out the top of the building and keeps the stairs cool. In the Pacific Northwest climate, this solution met the needs of an efficient building perfectly. It keeps the occupants healthy, lowers energy use, and is a beautiful design feature of the building. It is definitely one of the most remarkable features of the project.

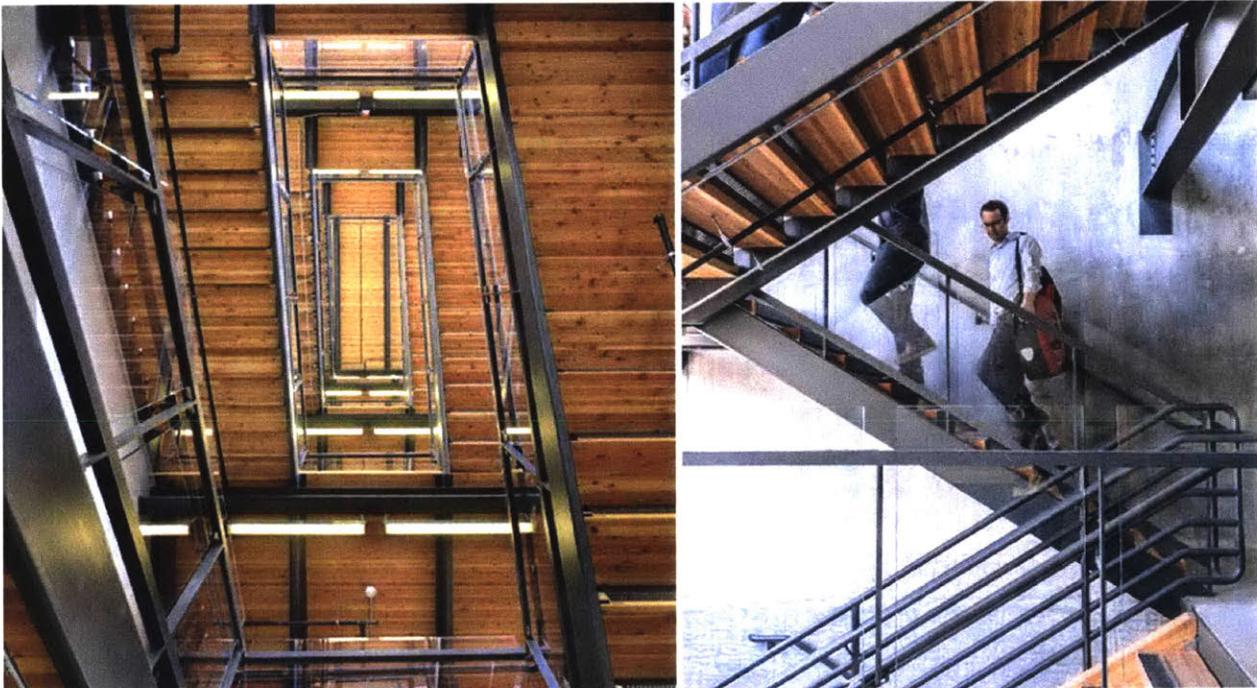


Exhibit 3: Bullitt Center Irresistible Staircase

Natural Ventilation²⁰⁴

The building was meant to use minimal energy in the HVAC system by facilitating natural airflow. The building was designed with operable windows, called parallel displacement windows, that are programmed to open and close automatically, allowing maximum ventilation. They can also be operated manually. If the windows are open, the air circulates into the space and out the way it came. If the windows are closed, a 100% outside air system ventilates the interior making sure that no air is recirculated within the building.

²⁰³ Thomas, 105,114,158.

²⁰⁴ Thomas, 130.

The windows are German-designed and automatically pop out laterally to create space for airflow. The windows are set to open when the outside air reaches 62°F. Because the windows were designed to only open when a temperature difference exists between inside and outside air, they created the perfect passive circulation system. Warm air would escape through the top of the windows while cool air would be drawn in through the bottom. This created a natural convection current that would quickly replace all the air in a room without the energy-consuming use of fans.

Bike Storage Room

The Bullitt Center has a bike storage room in the basement of the building and showers for tenants on each floor. Building occupants can bike, jog, or walk to work and have the ability to freshen up before a day at the office. Coupled with the lack of parking at the building, the design works to eliminate fuel-hungry means of transportation for tenants of the building.²⁰⁵

Car-Free Building

The building has no on-site parking; structured, surface, street, or otherwise. The building benefits from access to multiple city bus lines that connect residents to downtown and the surrounding neighborhoods. There are also new rail lines going in within walking distance of the building and various car-sharing locations where tenants can find a ride if they need one.²⁰⁶ The site has great walkability, and Walkscore.com gives them a 99 Walk Score, a 71 Transit Score, and an 85 Bike Score.²⁰⁷

Window Glazing²⁰⁸

The designers used triple-pane, argon-filled, low-E glass windows in the building. Overall, the building façade has 40% glazing coverage, meaning 40% of the building envelope is made up of windows. On the south side of the building where the building has its greatest sun exposure, the building is 60% glazing, allowing for more daylight to reach the interior space. There is no available data on U-value or SHGC.

Toxin-Free Materials²⁰⁹

As part of the Living Building Challenge, there is a list of materials, called the Red List, that cannot be included in the building because of their use of toxic or environmentally-unfriendly ingredients. The

²⁰⁵ Thomas, 55.

²⁰⁶ <http://casestudies.uli.org/bullitt-center/>, July 24, 2016.

²⁰⁷ <https://www.walkscore.com/score/bullitt-center-seattle-washington>, July 24, 2016.

²⁰⁸ Thomas, 92.

²⁰⁹ Thomas, 123-128.

Bullitt Center vetted more than 1,400 materials for inclusion in the project and nearly 900 were able to be used, while more than 500 different materials had to be excluded and alternatives had to be pursued. Although this gave the building a raw look that some people responded to negatively, it made for a healthier building for the tenants while allowing for durability and easier maintenance.

Another benefit of this process was the changed attitudes within the construction industry. The development team was able to work with suppliers and actually reformulate some of the most widely-used products in the construction industry. One example of this is the weatherproofing barrier. An ingredient called phthalates was included in the product, but after some back and forth the manufacturer, ProsoCo, was able to reengineer the product to exclude that harmful ingredient. Now, that ingredient has been removed across all the company's products and the formula is a healthier and safer version. This benefits both the workers installing it and the future occupants of the building.

Also, instead of using traditional PVC pipes and the usual metal connectors that typically contain lead, the building utilized ABS and/or HDPE pipes and used brass connectors where needed, which do not contain any lead.²¹⁰

Timber²¹¹

Timber is used for all framing above the second floor of the building. The timber was locally sourced from the Pacific Northwest close to the project, and was certified by the Forest Stewardship Council (FSC) based on how responsibly the source forest is managed. FSC wood comes from forests with more soil carbon, less erosion, more biodiversity and old growth, less herbicides, and less clear cutting.²¹² The benefit of timber beyond aesthetics is its carbon-negative nature. It contributes greatly toward allowing a building to be carbon-neutral.

Recycled Materials²¹³

Two examples of the project cutting down on waste are the plywood formwork for the concrete and the mesh tree fencing that protected existing trees on the site. The formwork used to pour concrete was gently used from another project and the only evidence of the reuse are a few imperfections on interior walls, which in turn provided a story about another sustainable element of the project. The fencing, which is inexpensive, but usually manufactured and shipped from China, was pulled from other job sites around Seattle, avoiding additional fuel consumption and materials being added to a landfill after the project was completed.

²¹⁰ Thomas, 133.

²¹¹ Thomas, 134-135.

²¹² <https://www.scsglobalservices.com/fsc-certified-responsible-forestry>, July 25, 2016.

²¹³ Thomas, 136.

Rainwater Capture

The Bullitt Center takes advantage of the rainy Seattle climate through rainwater capture. The roof of the building, which overhangs the building footprint and encompasses the entire site footprint, collects almost every drop of rainwater that falls on site. Beneath the photovoltaic array, a membrane roof channels that rainwater to a number of drain pipes that weave their way to the basement. The basement is home to a 56,000 gallon concrete cistern.²¹⁴ The size of the collection tank was determined by calculating how much water the building would use on an average day and then accounting for a drought of 100 days. This calculation allowed for nearly double redundancy, as Seattle has never gone more than 51 days without measurable rain in the recorded history of the city.²¹⁵

Bioswale & Green Roof²¹⁶

All the greywater from the sinks, showers, and taps in the building is directed to centrifugal filters on the first floor of the building, where the filters remove the larger particles left behind from biodegradable soap and other contaminants that have mixed with the water since leaving the potable taps. From there, the water is sent to a 500-gallon greywater tank, and then pumped to a green roof located on the third-floor terrace. The 800 square-foot man-made wetlands can process up to 300 gallons of greywater at a time. The green roof is full of rich soils and porous gravels that break down any organic matter or pathogens still left in the water. The plants on the green roof evapotranspire most of the water, and any overflow drips through an irrigation system that deposits the extra water into the bioswales that line the street-level entrance on the west side of the building. The rest of the remaining greywater drains through a vertical pipe to the ground level and is used for irrigation or infiltrates back into the native landscape and groundwater. No water from the site leaves through municipal sewer lines.

Greywater Treatment System

Rainwater that is collected is pumped through a series of fine ceramic filters before being introduced to ultraviolet light that eliminated contaminants, cysts, bacteria, and viruses. Lastly, a small amount of chlorine is added to the rainwater to satisfy regulatory requirements. As the water is delivered to drinking taps, shower heads and sink faucets, it is run through charcoal filters to remove that chlorine. Although chlorine is not exactly a sustainably-approved substance, the greater achievement of water reuse outweighed the use of the chlorine.²¹⁷

²¹⁴ Thomas, 63-64.

²¹⁵ www.seattleweatherblog.com, June 24, 2016.

²¹⁶ Thomas, 66-70.

²¹⁷ Thomas, 64.

Composting Toilets²¹⁸

The building is home to 32 foam-flush, waterless Phoenix toilets. The waste travels down nearly vertical pipes to the basement where composting tanks are housed. The upper tanks are filled with woodchips that combine with the liquid and solid waste and are periodically stirred to help release gasses and further the composition process. When the particles are small enough, they migrate into a lower tank. Approximately every 18 months, this lower tank is emptied and brought to a local composting company, where it is combined with sawdust and sold as fertilizer.

To eliminate odors in the occupant space, the bathrooms are negatively pressurized, drawing air from outside the bathroom directly into the toilet and down the vertical pipes to the basement tanks.

Pervious Pavement

The small amount of the site that is not covered by the building footprint is covered with pervious pavement to absorb any storm runoff that is not collected by the building's roof.²¹⁹ The building puts no water at all into the municipal sewer system.

As discussed above, the Bullitt Center is the first ever Living Building Challenge office building in the world. It may also be the most sustainable commercial building in the world. Its Energy Use Intensity (EUI) target was a 16 and its actual consumption during its monitoring year was a 10, at 85% occupancy. To give that number some context, LEED Platinum buildings designed to Seattle's relatively strict building code come in with EUI's around 34 and the average existing commercial building in Seattle has an EUI of 92. The work that went into this building was unquantifiable. It took an amazingly talented, focused and driven team to arrive at such an impressive end result. That is the type of passion that is required to get to net-zero energy and water design today. Hopefully as technologies continue to advance, the process gets easier and the Bullitt Center has paved the way for more buildings to reach a similar net-zero status.

²¹⁸ Thomas, 72-74.

²¹⁹ https://www.wbdg.org/references/cs_bullittcenter.php, July 24, 2016.

Case Study #2: The Darla Moore School of Business at the University of South Carolina, Columbia, SC²²⁰

The Darla Moore School of Business (DMSB) is located in the capital city of South Carolina, Columbia. The project was conceived to replace the aging business school and to match the strong reputation as a leader in international business. The building was built in 2014 with a budget of \$106.5 million. It is a 252,000 square foot project complete with 136 faculty offices, 35 classrooms with 2,554 seats, 40 meeting rooms, a trading floor, a café, a 250-seat lecture hall, a 500-seat auditorium that doubles as a performance space, and a library.

The building was designed to meet LEED Platinum standards, and is awaiting its certification. It was also chosen by the U.S. Department of Energy to partner with its national laboratories as part of its Net Zero Energy Commercial Building Partnership Program. This partnership allowed the development team to benefit from the expertise in energy technologies, building systems and design through a relationship with the Lawrence Berkeley National Lab.

The project was led by the building's namesake, Darla Moore, who hand-selected the design team, starting with the architect. The buildings was designed by Rafael Viñoly out of New York City. He was picked for his ability to blend new building with their surroundings, similar to what he was able to do at University of Chicago's business school, located next to Frank Lloyd Wright's Robie House.²²¹ The engineering firm on the project was Stevens & Wilkinson, a local architecture and engineering firm with offices in Columbia, South Carolina, and Atlanta, Georgia. The process also involved the Department of Energy Technical Expert team, which included Steven Winter Associates, Inc., and The Weidt Group, Inc., as the Measurement and Verification Contractor.²²²

The delivery method of the project was Design-Build, with the project team coming together in the early stages of planning to design the project. Accelerated site and structural design packages were issued to the design team in order to speed the process along and meet an expedited schedule for the construction start date as well as the delivery date. The site had a number of complex design elements including: elevation change, transfer columns, site soil concerns, and flexible design to leave options for potential future pavilions on-site.²²³

Energy modeling was done by the Department of Energy's modeling software, EnergyPlus. The school also used 3D modeling to anticipate how students would move through it, in hopes of making it a more collaborative space.²²⁴ Many of the energy-efficient measures were being incorporated into the building as the Technical Expert team was evaluating them in parallel, which made assessment somewhat

²²⁰ Hennessey, et. al, July 2016.

²²¹ <http://www.thestate.com/news/local/education/article13880771.html>, July 25, 2016.

²²² https://buildings.lbl.gov/sites/all/files/lbnl-1003926_usc_darla_moore_rev.pdf, July 5, 2016.

²²³ <http://cenews.com/article/10209/smart-design-improves-building-efficiency>, July 25, 2016.

²²⁴ <http://www.thestate.com/news/local/education/article13880771.html>, July 25, 2016.

difficult. Verification and energy savings were of the highest priorities to the development, so a Measurement and Verification Plan and a Monitoring Plan were put in place to streamline a process for assessing the performance of all the sustainable interventions as soon as the building became operational.

It should be noted that the climate in Columbia, South Carolina is very different from that of Seattle or Boston. It is a cooling-dominated climate and rarely drops below freezing. The humidity is often in the 90%-range throughout the entire summer,²²⁵ and the tourism slogan of the city is, “Famously Hot”.²²⁶ To be net-zero in this type of climate, the renewable energy supply needed is much larger than in Northern, heating-dominated climates.

Energy savings were most impacted by the heating, ventilation and air conditioning efficiency measures that were deployed within the building. Based on modeling, the building would consume 52% less energy for cooling and 63% less energy for heating than the baseline model, which was based on ASHRAE standards. In addition, interior lighting which represented 12% of the total energy consumption, was able to be reduced by 40% due to daylighting, sensors, dimmers and energy-efficient lighting fixtures and bulbs.²²⁷ According to reports, the building was estimated to save approximately \$400,000 in energy and water bills on an annual basis.²²⁸ Overall water use was expected to be reduced by 50% due to efficient design and rainwater capture.²²⁹

Below is a table containing a list of the interventions included in the design and development of the Darla Moore School of Business at the University of South Carolina. Each intervention is explained in more detail on the following pages.

Energy	Design	Materials	Waste & Water
Hybrid HVAC System Enthalpy Wheel Energy-Efficient Elevators Daylight & Occupancy Sensors Efficient Electrical System Efficient Office Equipment & Lighting Smart Meters & Occupant Behavior Renewable Energy (Future)	Green/Cool Roof Passive Self-Shading Irresistible Staircase Glazing Reduction Bike Storage	Reflective Surfaces Sustainable Timber Recycled Materials Regional Materials Toxin-Free Materials	Rainwater Collection High-Efficiency Water Fixtures

Table 6: Darla Moore School of Business Sustainable Interventions

²²⁵ <https://weatherspark.com/averages/29988/Columbia-South-Carolina-United-States>, July 25, 2016.

²²⁶ <http://www.columbiacvb.com/media/photos-logos/famously-hot/>, July 25, 2016.

²²⁷ https://buildings.lbl.gov/sites/all/files/lbnl-1003926_usc_darla_moore_rev.pdf, July 5, 2016.

²²⁸ <http://www.environmentalleader.com/2012/02/21/largest-net-zero-building-in-the-world/>, July 25, 2016.

²²⁹ <http://bstonegroup.com/business-school-on-path-to-becoming-largest-net-zero-energy-building-in-southeastern-u-s/>, July 25, 2016.



Exhibit 4: Darla Moore School of Business Exterior Façade



Exhibit 5: Darla Moore School of Business Interior Courtyard with Irresistible Staircase

Hybrid HVAC System

The hybrid HVAC system takes advantage of the climate as much as possible and tries to mitigate excess energy waste. The system is engineered with a combination of under-floor radiant air, chilled beams and variable-air-volume handling units. A separate HVAC system was put in place for the large auditorium to reduce sound and keep the acoustics of the space as pure as possible. Stevens & Wilkinson coordinated with an acoustic consultant to meet the desired acoustic performance.²³⁰

The system is set up to have many different localized zones because the building is so spread out and sees light and heat coming from a number of different angles. These zones allow for more targeted heating and cooling and have individual thermostats that allow occupants to control their surroundings. The cooling system is a chilled beam system that uses chilled water from a localized plant on campus. The water is then recycled for irrigation or toilet use. Heating is very minimal because of the climate, and is steam-based. There is also a computer-controlled system that monitors the heating and cooling and can help run the system as efficiently as possible. It alerts maintenance to any issues and points them directly toward the problem so time and energy are not wasted.

One unique feature of the monitoring system is its ability to track CO₂. Through the CO₂ levels in the room it can distinguish whether the room is vacant or occupied. If the room is vacant, the system will reduce airflow, and if it is full, it increases it to get more fresh air into the space. The system can also monitor the quality of the outside air that is being used for ventilation. If the outside air is not fresh, it will stop the air from coming in.

Enthalpy Wheel

Thermal enthalpy wheels are used in the HVAC system for heat recovery. They are incorporated in the outside air units to ensure that as exhaust air leaves the building, as much energy is recycled within the air stream to the incoming supply air.²³¹

Energy-Efficient Elevators

The building also makes use of energy-efficient and space efficient elevators. They are machine room-less, gear-traction elevators with 10-12 horsepower motors.

Daylight & Occupancy Sensors

Daylight is utilized throughout much of the building. The building is designed in a block “O” shape so it receives daylight from all sides. It is also very glass-heavy on the façade, except for the two top floors.

²³⁰ <http://cenews.com/article/10209/smart-design-improves-building-efficiency>, July 25, 2016.

²³¹ https://buildings.lbl.gov/sites/all/files/lbnl-1003926_usc_darla_moore_rev.pdf, July 25, 2016.

The open concept floorplates allow for maximum daylight penetration, not blocked by office walls or other obstructions. Additionally, there are skylights in the roof that allow vertical light penetration. The central courtyard opens up the entire building and allows for a very well-lit building all around.

Efficient Electrical System

The building's electrical system was designed to be more efficient than traditional systems. The system is designed to have two vertical power feeders to opposite corners of the building, so there are two separate power feeds. The distribution of energy between two feeds allows for equal distribution across the building. Running feeds up two different corners of the building, the distribution is equal across each floor. Transformers on each floor control the voltage and send the electricity to electrical panels. Splitting the load in two allows for easier distribution, ease of maintenance, and separation of circuits that create redundancy if one side of the building were to go down. This set up also allows for a decreased use of electrical wiring as well, a cost and resource savings.

Efficient Office Equipment

Just like we saw in the Bullitt Center, all the office equipment is energy-efficient. All appliances and computers are ENERGY STAR-rated.²³² The school also chose to reduce energy-intensive on-site server use in exchange for cloud-based technology. This allowed them to reduce the energy draw that comes with large servers. No staff members are allowed to bring in their own appliances, like a mini-fridge for their office. Instead, all appliances are provided in the communal kitchen and are energy-efficient. This way they avoid older, less efficient appliances making their way into the building and drawing unnecessary energy.

Efficient Lighting

Now common in most new buildings, efficient lighting fixtures were installed. All lights in the building are either LED lights or T5 linear fluorescents. The lights are also on timers and sensors, so they go off if the room is empty and the entire building light system shuts off after a certain time of night to make sure no energy is wasted overnight while the building is empty. Energy savings from this efficient lighting is 40% compared to baseline modeling.

²³² https://buildings.lbl.gov/sites/all/files/lbnl-1003926_usc_darla_moore_rev.pdf, July 25, 2016.

Smart Meters

The building is tied to a very advanced energy monitoring system through Johnson Controls. It monitors building plug loads, CO₂, heating, cooling, fan motors, elevators, interior and exterior lighting, kitchen equipment, and domestic water.²³³ Anyone with the link can see how the building performs on a daily basis. It shows the current use, the previous week's use and how the building is doing comparably. You can adjust the timeframe to look at month-over-month consumption or year-over-year consumption as well²³⁴.

Occupant Behavior

Because occupants were moving from the old business building to the new one, it created a unique opportunity to begin educating the occupants prior to taking occupancy in the project. Staff began orientations to change the cultural attitude of those occupants. They started shredding, scanning and recycling plans, trying to move to a non-paper environment among the faculty and staff. They also offered training to faculty, staff and students about the new facility's features, technology, and operations and hired experts and student ambassadors to offer assistance in the early days of the transition.

Renewable Energy

The goal of the building was net-zero energy use, but as of today, there have been no renewable energy sources installed on site. The building has been designed and developed to net-zero ready standards, meaning it does everything it can to minimize energy use. When renewable energy sources are installed, the amount of energy capture will be at a level which makes net-zero status feasible. The people I spoke with believe that based on the energy load and the size of the site that net-zero status is attainable, however, there are no immediate plans for installation of renewable energy sources.

Green/Cool Roof

The roof on the building is designed to serve multiple purposes. First, it has four covered pavilions for events and collaboration opportunities. But the energy efficiency is derived from a combination of a green roof and cool roof design. Part of the roof is covered in native species that are adapted to the hot South Carolina climate and do not require an overabundance of water. This vegetation is able to remove 80% of the total suspended solids from the stormwater before that water is returned to the ground or to local waterways. The remaining roof space is covered with a white reflective surface that helps to reduce heat gain to the building through the roof as well as reduce the heat island effect for the entire site.

²³³ <http://cenews.com/article/10209/smart-design-improves-building-efficiency>, July 25, 2016.

²³⁴ <http://www.bedashboard.com/kiosk/home/index/29/3021/rollover>, July 13, 2016.

Passive Self-Shading

The building is designed to act as its own sunshade. Each level of the building gets bigger as you move upward, designed as an inverted pyramid of sorts. The floors are cantilevered out over one another so that the larger floorplate of the floor above shields the lower floor from solar heat gain. This stacked design allows the use of less energy for cooling in this cooling-dominated climate. Within the interior courtyard, there are also covered walkways and large palmetto trees that shade the area to make a more comfortable atmosphere for students to congregate.

Irresistible Staircases

Following the lead of the Bullitt Center, the Moore School building designed staircases that lead to the upper floors of the building to encourage students to avoid elevator use. The stairways are located in the open interior courtyard so students can get to the upper floors without having to go through the lobby of the building. The stairways are designed with a gradual rise to allow for less exertion while climbing them to your next class.

Glazing Reduction

On the 3rd and 4th floors of the building, where the façade is more exposed to sunlight, the developers and designers reduced the use of glazing by 30%. The timber façade on these floors catches the thermal heat and acts as thermal mass to keep the heat from passing into the building. This thermal mass helps regulate temperature as was explained in Part II. Sunlight still comes through from the roof's skylights to light these upper floors, providing for natural light. The glazing that is on the lower floors varies depending on its location. On south and north facing sides of the building, the transmittance of visible light is higher, closer to 50%. On the east and west facing sides of the building, the transmittance is lower, around 20%, to reduce glare and heat gain.

Bike Storage

The building is surrounded by bike racks on all sides, encouraging students to bike instead of drive. While there is parking available in lots and structures close to the building, the building itself is car-free. These outdoor bike racks are not as nice as an indoor bike room, and the building is not equipped with showers, but it is located right across from the main workout facility on campus, the Strom Thurmond Center, so if people wanted to bike to the building and then shower before class or meetings, it is possible.

Reflective Surfaces

In addition to the roof, there are also reflective surfaces built into the rest of the site. All the sidewalks and paved areas are made up of a light-colored surface that reflects light and heat and keeps the ground level from becoming overheated. The entire interior courtyard is made up of light-colored surface materials.

Sustainable Timber

The building was designed using a large amount of timber as a building material. All the wood in the building was sustainably harvested from approved forests and came from the local area within North and South Carolina.

Recycled & Local Building Materials

The building was developed using recycled and local materials. At least 30% of the building materials used in the project contained recycled material. In addition, over 30% of the materials came from local suppliers, which reduced the carbon emissions from transportation.

Toxin-Free Materials

The building was developed using as many toxin-free materials as possible. In addition, the building cleaning staff uses 100% green cleaning supplies to maintain the building.

Rainwater Collection

The roof acts as a collection device for rainwater. Rainwater is collected and guided to a 20,000 gallon tank in the basement of the building. This tank feeds irrigation systems for the green roof as well as all the on-site landscaping. In addition to irrigation, the rainwater collection feeds into the water system and that greywater is used in approximately 25% of the toilets on site.

High Efficiency Water Fixtures

Like every new building nowadays, all the sink, fountain, and toilet fixtures are low-flow design with reduced water use supplemented by higher water pressure.

The Darla Moore School of Business took on a large challenge in striving for net-zero development. The modeled EUI of 68 kBtu/ft² is a 48% reduction from the baseline of 130, based on ASHRAE standards from the 2007 code.²³⁵ Even with the 48% reduction in energy use, there is a large amount of energy that needs to be captured to offset the daily activities in such a large institutional building. Also, with building occupants changing on an annual basis, teaching new students about the challenges and benefits of the building can be truly difficult. Students are bringing in their own computers, charging off the building's systems with no ability for the building owners to control those behaviors. The building will likely achieve LEED Platinum status in the near future, but net-zero energy attainment has been delayed for the near-term. It is this dichotomy that this thesis strives to bring to the reader's attention. While Platinum buildings are a step in the right direction, there is still a very long way to go to reach a truly sustainable built environment. And the gap between reaching Platinum status and reaching net-zero can be a large one.

²³⁵ https://buildings.lbl.gov/sites/all/files/ellen_thomas_lbnl-6904e.pdf, July 25, 2016.

Part IV: U.S. LEED Platinum Building Analysis

Leadership in Energy and Environmental Design, or LEED, is a building certification system started by the United States Green Building Council and recognized as the standard for sustainable development. It is the most widely used green building rating system in the United States and second most used in the world. Buildings earn credit for energy efficiency, air quality, water use reduction, and improved quality of life for occupants. According to the USGBC website:

LEED certification provides independent verification of a building or neighborhood's green features, allowing for the design, construction, operations and maintenance of resource-efficient, high-performing, healthy, cost-effective buildings. LEED is the triple bottom line in action, benefiting people, planet and profit.²³⁶

The rating system scores buildings on a scale of 110 points, and the scale has four certification levels: Certified, Silver, Gold, and Platinum. A score of 80 or more must be achieved to reach the Platinum level. There are different versions of the rating scale, based on the type of building, including new construction, existing buildings, commercial interiors, and homes. The data included in this section is based on the 2009 version of the rating system. LEED 2009 is the 4th iteration of the LEED certification system, following Version 1.0, Version 2.0, and LEED New Construction 2.0.²³⁷

For this analysis, the Green Building Information Gateway (GBIG) database provides a comprehensive resource for LEED point scoring and certification levels. The data was manually extracted from the GBIG database and filtered based on a number of criteria. The data set is specific to what would most likely match net-zero development. It consists of new construction and existing buildings. The new buildings are either ground up development or full gut renovation and repurposing of older structures. The other buildings included in the set are existing buildings that have been updated for maximum energy efficiency with a focus on operations and maintenance. The sample set consists only of the highest-achieving LEED buildings, which are the Platinum buildings. While LEED Platinum status begins at 80 points, the data set only includes buildings with scores of 85 or higher. This was done to eliminate buildings that just barely met the threshold, to avoid looking at buildings that were doing the bare minimum to reach Platinum, and instead looking at buildings that were pushing the boundaries of sustainable development further than the rest. The data was further confined to corporate-owned and investor-owned projects. The reason for doing so was to determine what is commercially diffusible for the commercial real estate realm with respect to sustainability. These buildings are the most telling because their investment horizons are similar to that of typical commercial investors. The sample set is comprised of 42 buildings, 14 of which

²³⁶ <http://leed.usgbc.org/leed.html?gclid=CNC4yJGWjM4CFpahgoddOkMzA>, July 24, 2016.

²³⁷ <http://enviroinstitute.org/wp-content/uploads/2012/09/GREEN-BUILDING-A-Retrospective-History-of-LEED-Certification-November-2012.pdf>, July 26, 2016.

are new construction and 28 of which are existing buildings that have been upgraded to sustainable levels of operation.

The summary of the building set is outlined in the following table. The average building size is nearly 300,000 square feet, although half the buildings are less than 160,000 square feet. It shows that new buildings earn points in fewer credit categories than existing buildings, but the new buildings in the set had a slightly higher average score. The average score for the entire set was 87.5 out of 110, a percentage score of 79.5%. It is somewhat surprising that the best buildings in the LEED rating system are so far from the top achievable score. More summary data is available in the table below.

LEED Platinum Building Set LEED Score > 85	
Buildings	42
Avg. Building Size	297,620
Median Building Size	158,902
Total LEED Credit Categories	
New	49
Existing	50
Average LEED Categories Satisfied	
New (#)	35.9
New (%)	73.3%
Existing (#)	39.1
Existing (%)	78.3%
Standard Deviation (Credit Categories)	
New	2.8
Existing	2.5
Average LEED Points	
New	87.9
Existing	87.3
Standard Deviation (Points Earned)	
New	3.3
Existing	2.2

Table 7: Summary of Sample Building Set

The purpose of analyzing the data of the top-tier LEED buildings is to draw comparisons between what is currently the standard for sustainable development within the built environment and the net-zero interventions and buildings outlined in Parts II and III. Are there opportunities for the LEED program to further the diffusion of net-zero energy and water consumption interventions and push developers toward more sustainable and operationally efficient options?

We have broken down the buildings into two sets: new buildings and existing buildings. These two distinct sets have different LEED certification criteria and different scoring metrics. The full data is provided later in the section.

New Buildings

New buildings have a possible 49 credits in which they can achieve points, from wastewater technology to innovation in design, as well as energy, recycled materials, type of electricity supplied, water reduction, and myriad more. These credits are broken into five categories: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, and Indoor Environmental Quality. The points are weighted based on potential impacts to the environment and the benefits to human health and wellness. LEED for new construction focuses on the design and construction activities for new ground-up construction as well as major renovations of existing buildings. From the LEED New Construction booklet:

The impacts are defined as the environmental or human effect of the design, construction, operation, and maintenance of the building, such as greenhouse gas emissions, fossil fuel use, toxins and carcinogens, air and water pollutants, indoor environmental conditions. A combination of approaches, including energy modeling, life-cycle assessment, and transportation analysis, is used to quantify each type of impact.²³⁸

There is also a list of seven prerequisites that must be fulfilled to qualify for LEED certification at any level. Those prerequisites are: Construction Activity Prevention; Water Use Reduction; Fundamental Commissioning of Building Energy Strategies; Minimum Energy Performance; Fundamental Refrigerant Management; Minimum Indoor Air Quality Performance; and Environmental Tobacco Smoke Control. The specifics of each of these prerequisites and all available credits are available in the source material.²³⁹ These prerequisites set the baseline for all LEED-aspiring projects in terms of construction standards, energy use, air quality, and water use. Project teams work with the Green Building Certification Institute (GBCI), a subsidiary of the USGBC, to register projects and have them evaluated for certification.

There were 15 credits in which every new building in the sample set achieved points, each of which is explained below. In addition, there were three credits in which less than 50% of these top-tier buildings scored points. The credits that were underutilized are also outlined below. The following categories were fulfilled by all new buildings:

Optimize Energy Performance (19 Points) – This is the basis of net-zero development. Optimizing energy performance is the reduction of energy loads as much as possible through optimization of all systems. The buildings that reached Platinum status in this set scored a minimum of 15 out of 19 and averaged 18.3 points. This means that they reduced their energy use by more than 44% on average over baseline building performance.²⁴⁰

²³⁸ LEED 2009 for New Construction and Major Renovations, 13.

²³⁹ LEED 2009 for New Construction and Major Renovations, 11.

²⁴⁰ LEED 2009 for New Construction and Major Renovations, 48.

Green Power (2 Points) – This credit requires a minimum two-year contract with your grid-sourced energy provider that at least 35% of the building’s electricity will come from renewable sources, encouraging renewable energy production.²⁴¹

Construction Indoor Air Quality (IAQ) Management Plan - During Construction (1 Point) – This pre-occupancy intervention is meant to protect the construction workers in the process of constructing the building. It requires an air handling system on site during the work with proper, approved filtration devices. It has little correlation to energy efficiency and net-zero development.²⁴²

Low-emitting materials - adhesives and sealants (1 Point) – This intervention is aimed at keeping air quality high and maintaining the health of occupants.²⁴³

Low emitting materials - paints & coatings (1 Point) – Again, this is aimed at keeping the atmosphere of the building clean, as well as keeping harmful materials from being manufactured and introduced into the built environment.²⁴⁴

Low emitting materials - flooring systems (1 Point) – By using these low emitting materials, building owners and developers are sending messages to suppliers and manufacturers that this is the future. Non-toxic or less toxic alternatives are being used in every high-scoring LEED building in the sample provided. Although it is healthy for the environment, it does not align with the goals of net-zero.²⁴⁵

Innovation in Design (5 Points) – Creative design can be expressed outside of the confines of the LEED requirements through the Innovation in Design criteria. This allows developers, architects, etc., to do something innovative that is not strictly detailed in the LEED program. Each innovative strategy can earn 1 point, up to a maximum of 5 points earned. The average Innovation in Design for the new building sample set was 4.7, meaning most of the buildings maxed out their opportunity for innovative design. However, there is no outline for measuring the contribution to environmental, energy or water impacts for these points.²⁴⁶

LEED Accredited Professional (1 Point) – This is earned by having at least 1 LEED AP on the project team. These projects are much easier if you are working with someone who is familiar with the process. Again however, this point does not specifically lead to any environmental impact.²⁴⁷

Construction waste management (2 Points) – Large development projects create dumpsters full of waste on a daily basis. It is the goal of this intervention to reduce and recycle those materials instead of

²⁴¹ LEED 2009 for New Construction and Major Renovations, 60.

²⁴² LEED 2009 for New Construction and Major Renovations, 76.

²⁴³ LEED 2009 for New Construction and Major Renovations, 79.

²⁴⁴ LEED 2009 for New Construction and Major Renovations, 81.

²⁴⁵ LEED 2009 for New Construction and Major Renovations, 82.

²⁴⁶ LEED 2009 for New Construction and Major Renovations, 95.

²⁴⁷ LEED 2009 for New Construction and Major Renovations, 96.

sending them to the landfills. At a minimum, 50% of all construction waste must be recycled to earn 1 point, and more than 75% must be recycled to achieve the 2 points.²⁴⁸

Recycled Content (2 Points) – This intervention is determined by the weight of all the materials used in the project. The goal is to use more than 10% (1 pt.) or 20% (2 pts.) recycled content in building materials. A wide range of materials can be included, like concrete and wood, but mechanical, electrical and plumbing materials need to be virgin materials for the safety of the project. This is also included in the net-zero interventions in Part II.²⁴⁹

Regional Materials (2 Points) – A building can earned points if at least 10% of materials are sourced from within 500 miles of the project. This encourages local materials and a reduction in energy costs and impacts for transporting the materials. Specifically, it is the use of materials extracted, harvested, recovered or manufactured within that distance. For 2 points, at least 20% of the materials need to be regionally-sourced.²⁵⁰

Site Selection (1 Point) – There are a number of things that need to be avoided in order to earn the site selection credit. Things like prime farmland, locations prone to flooding, habitats of threatened or endangered species, previous publicly-owned park land, wetlands, or undeveloped land within 50 feet of a body of water are all on the list of things that will negate this credit from being earned.²⁵¹

Innovation: Building exterior and hardscape management plan (1 Point) – The point of the exterior and hardscape management plan is to create environmentally sensitive, low-impact buildings and hardscapes that preserve the surrounding natural landscape and ecology. A good plan should include reduced harmful chemical use, energy and water waste, air pollution, solid waste and chemical run-off. In fewer words, the cleaning and maintenance of the site exterior should be environmentally friendly.²⁵²

Alternative transportation - low-emitting & fuel-efficient vehicles (3 Points) – One of the easier credits to receive, it requires that 5% of the parking spaces be labeled for low-emitting and fuel-efficient vehicles and given priority parking spaces.²⁵³

Water use reduction (4 Points) – One of the most important sustainable strategies is the reduction in water use, just like optimizing energy performance. To achieve this credit under LEED, a building has to reduce its water use by at least 30% below the baseline calculated for the building. There are detailed instructions under the program for the calculation of this baseline.²⁵⁴

²⁴⁸ LEED 2009 for New Construction and Major Renovations, 64.

²⁴⁹ LEED 2009 for New Construction and Major Renovations, 66.

²⁵⁰ LEED 2009 for New Construction and Major Renovations, 67.

²⁵¹ LEED 2009 for New Construction and Major Renovations, 18.

²⁵² LEED 2009 for New Construction and Major Renovations, 19.

²⁵³ LEED 2009 for New Construction and Major Renovations, 23.

²⁵⁴ LEED 2009 for New Construction and Major Renovations, 40.

The following technologies were utilized in under 50% of the 14 top LEED Platinum buildings.

Rapidly Renewable Materials (1 Point) – Rapidly renewable materials are those that are made from agricultural products that can be harvested within a 10-year life cycle. The credit requires that 2.5% of the total value of the building materials come from these resources.²⁵⁵ Only 3 of the 14 buildings were able to accomplish this. Some of the materials that are considered rapidly renewable are bamboo, cork, linoleum, cotton batt insulation, and certain fabrics.²⁵⁶

Site Development - protect or restore habitat (1 Point) – The benefits of this credit do not seem to outweigh the cost, especially in locations where FAR or height restrictions come into play. It requires a certain amount of the site to be left undisturbed or restored. But with land at a premium in dense urban areas, the tradeoff could be enormous to protect 50% of the site (excluding the building footprint) when there are needs for parking, circulation, access, etc.²⁵⁷

Innovative Wastewater Technologies (2 Points) - The goal of this intervention is to reduce the amount of wastewater that ends up in the municipal sewer and treatment system. The credit is earned by reducing potable water use for building sewage by 50% or by treating 50% of the wastewater on-site. Only 5 of the 14 new buildings included any type of innovative wastewater technology. The costs of installing a system and treating waste water on site are more expensive than allowing the water to be treated through the public sewer system. This is one of the interventions that is more valuable externally to the community than it is to the building itself. Treating wastewater on-site does not provide any great value to a building. It is one more system to maintain, more training that is needed for maintenance staff and additional risk taken on by ownership because of potential harm to building occupants due to mistreatment. There is no way to value the reduced burden to the municipality in a traditional sense, so this is one intervention that we are seeing many building owners forgo.²⁵⁸

On the next page is the full data for the new buildings in the sample set:

²⁵⁵ *LEED 2009 for New Construction and Major Renovations*, 68.

²⁵⁶ <http://www.buildings.com/article-details/articleid/9123/title/regional-and-rapidly-renewable-materials.aspx>, July 19, 2016.

²⁵⁷ *LEED 2009 for New Construction and Major Renovations*, 26.

²⁵⁸ *LEED 2009 for New Construction and Major Renovations*, 39.

Intervention	# of Points	# of Buildings to Get Credit	% of Buildings to Get Credit
Optimize energy performance	19	14	100.0%
On-site renewable energy	7	13	92.9%
Enhanced commissioning	2	11	78.6%
Enhanced refrigerant management	2	10	71.4%
Measurement and verification	3	9	64.3%
Green power	2	14	100.0%
Outdoor air delivery monitoring	1	11	78.6%
Increased ventilation	1	10	71.4%
Construction IAQ management plan - during construction	1	14	100.0%
Construction IAQ management plan - before occupancy	1	7	50.0%
Low-emitting materials - adhesives and sealants	1	14	100.0%
Low-emitting materials - paints and coatings	1	14	100.0%
Low-emitting materials - flooring systems	1	14	100.0%
Low-emitting materials - composite wood and agrifiber products	1	12	85.7%
Indoor chemical and pollutant source control	1	10	71.4%
Controllability of systems - lighting	1	12	85.7%
Controllability of systems - thermal comfort	1	7	50.0%
Thermal comfort - design	1	13	92.9%
Thermal comfort - verification	1	12	85.7%
Daylight and views - daylight	1	8	57.1%
Daylight and views - views	1	7	50.0%
Innovation in design	5	14	100.0%
LEED Accredited Professional	1	14	100.0%
Building reuse - maintain existing walls, floors and roof	3	7	50.0%
Building reuse - maintain interior nonstructural elements	1	1	7.1%
Construction waste management	2	14	100.0%
Materials reuse	2	1	7.1%
Recycled content	2	14	100.0%
Regional materials	2	14	100.0%
Rapidly renewable materials	1	3	21.4%
Certified wood	1	8	57.1%
Regional Priority	4	0	0.0%
Site selection	1	14	100.0%
Innovation: Building exterior and hardscape management plan	5	14	100.0%
Innovation: Integrated pest management, erosion control, and landscape management plan	1	9	64.3%
Alternative transportation - public transportation access	6	13	92.9%
Alternative transportation - bicycle storage and changing rooms	1	13	92.9%
Alternative transportation - low-emitting and fuel-efficient vehicles	3	14	100.0%
Alternative transportation - parking capacity	2	10	71.4%
Site development - protect or restore habitat	1	4	28.6%
Site development - maximize open space	1	8	57.1%
Stormwater design - quantity control	1	9	64.3%
Stormwater design - quality control	1	8	57.1%
Heat island effect - nonroof	1	9	64.3%
Heat island effect - roof	1	13	92.9%
Light pollution reduction	1	8	57.1%
Water efficient landscaping	4	12	85.7%
Innovative wastewater technologies	2	5	35.7%
Water use reduction	4	14	100.0%

Table 8: LEED New Building Credits – GBIG Sample Set

Existing Buildings

Existing buildings are treated differently under LEED, falling under the LEED for Existing Buildings Operations and Maintenance point system. The scale is still 110 points, but the credits are different in some cases. Existing buildings have a possible 50 categories in which they are able to score points. However, these categories are more focused on operations and building maintenance. The system is used to certify the sustainability of the ongoing operations of an existing building. This points system is less similar to the net-zero interventions discussed in Part II than the New Construction LEED guidelines

previously outlined above. There is more focus on monitoring, creating management plans, and performance measurements, and scoring can be accomplished without taking any consumption-altering steps in some cases.

There were 11 categories in which every new building in the sample set scored points, explained below. Because of the overlap with some of the new building categories, not every category is explained in depth. There were also 14 categories that at least 85% of the buildings scored points in and those have been listed as well.

Of the 28 existing buildings, the following categories were fulfilled by all:

Optimize energy efficiency performance (18 Points) – Previously discussed.

Existing building commissioning - investigation and analysis (2 Points) – This category requires that building owners and operators run analyses on the current performance of the building pre-renovation. This allows building owners to understand where energy is being used and how to reduce that use. It allows for educated next steps and the formulation of a plan to achieve optimal energy efficiency, but requires no actual action.²⁵⁹

Green cleaning - high performance green cleaning program (1 Point) – To achieve this credit, a building must have a cleaning program that uses sustainable cleaning products, proper training for maintenance staff, and a minimal use of chemicals. It is about the health of the building and its occupants, as the misuse of products can cause contamination of the air supply as well as damage to the building and its systems.²⁶⁰

Green cleaning - custodial effectiveness assessment (1 Point) – This credit is a simple assessment of the custodial staff and the condition of the building. It is meant to “reduce the exposure of building occupants and maintenance personnel to potentially hazardous chemical, biological and particulate contaminants...” Again, no action is required after the assessment.²⁶¹

Green cleaning - purchase of sustainable cleaning products and materials (1 Point) – This requires the purchase of “green” cleaning products as well as recycled content paper products. The specific list of criteria for cleaning products can be found in the LEED literature.²⁶²

Innovation in operations (4 Points) – Similar to Innovation in Design, this credit can be achieved by using strategies that are outside the framework of the LEED Existing Building guidelines and have a

²⁵⁹ LEED 2009 for Existing Buildings Operations and Maintenance, 31.

²⁶⁰ LEED 2009 for Existing Buildings Operations and Maintenance, 77.

²⁶¹ LEED 2009 for Existing Buildings Operations and Maintenance, 78.

²⁶² LEED 2009 for Existing Buildings Operations and Maintenance, 79.

significant positive impact on the environmental-friendliness of the building. The average score in the sample building set was 3.8 out of 4.²⁶³

Sustainable purchasing - reduced mercury in lamps (1 Point) – The goal of this credit is to reduce the amount of toxic mercury in the building. To achieve this credit, the building must use bulbs that contain below a certain level of mercury, and 90% of the building’s lights must meet this threshold.²⁶⁴

Solid waste management - waste stream audit (1 Point) – Audit the waste stream of the building, taking into consideration type of waste and the weight of each type that is generated by the site to establish a baseline. Once a baseline is established, identify opportunities to reduce the amount and impact of the waste. Once again, beyond assessment and identification, actual action is not required to earn points.²⁶⁵

Alternative commuting transportation (15 Points) – The goal of this credit is to reduce the number of commuting roundtrips. The baseline is single-occupant car commuting for every person at the building, and alternatives include telecommuting, compressed workweeks, mass transit, ridesharing, human-powered conveyance (walking or biking), van-pools and low-emitting fuel-efficient or alternative-fuel vehicles. The average score for the buildings in the set was 12.6, which equates to a reduction in conventional commuting trips by more than 55%. However, considering many people in urban areas take mass transit or walk/bike to work, many buildings may already be achieving a reduced commuting trip count without the need for LEED encouragement.²⁶⁶

Water performance measurement (2 Points) – For 1 point, the building needs to have in place a permanently installed water meter that measures total water use. For the additional point, a water meter needs to be installed that services a distinct piece of the water use system, whether it be irrigation, indoor plumbing fixtures, cooling towers, domestic hot water, or some other water process.²⁶⁷

Additional indoor plumbing fixture and fitting efficiency (5 Points) – Reduce water use further from the baseline set in the LEED Existing Building guidelines. The guidelines specify that all plumbing fixtures meet the standards set by the Uniform Plumbing Codes 2006. A 30% reduction below this baseline earns the entire 5 point credit, which all the existing buildings in our sample set achieved.²⁶⁸

²⁶³ LEED 2009 for Existing Buildings Operations and Maintenance, 85.

²⁶⁴ LEED 2009 for Existing Buildings Operations and Maintenance, 50.

²⁶⁵ LEED 2009 for Existing Buildings Operations and Maintenance, 53.

²⁶⁶ LEED 2009 for Existing Buildings Operations and Maintenance, 5.

²⁶⁷ LEED 2009 for Existing Buildings Operations and Maintenance, 18.

²⁶⁸ LEED 2009 for Existing Buildings Operations and Maintenance, 19.

In addition to unanimous achievement in the above 11 categories, the following categories were completed by at least 85% of the buildings in the sample set:

- Existing building commissioning – implementation (2 Points)
- Emissions reduction reporting (1 Point)
- Green cleaning - sustainable cleaning equipment (1 Point)
- Green cleaning - indoor integrated pest management (1 Point)
- LEED Accredited Professional (1 Point)
- Solid waste management - ongoing consumables (1 Point)
- Solid waste management - durable goods (1 Point)
- Building exterior and hardscape management plan (1 Point)
- Indoor air quality best management practices - indoor air quality management program (1 Point)
- Indoor air quality best management practices - reduce particulates in air distribution (1 Point)
- Controllability of systems – lighting (1 Point)
- Green cleaning - indoor chemical and pollutant source control (1 Point)
- Sustainable purchasing – furniture (1 Point)
- Integrated pest management, erosion control, and landscape management plan (1 Point)

Less than 50% of the buildings in the existing building set scored points in the following categories:

- Stormwater quantity control (1 Point)
- Site development - protect or restore open habitat (1 Point)
- Sustainable purchasing – food (1 Point)
- Sustainable purchasing - facility alterations and additions (1 Point)
- Occupant comfort - thermal comfort monitoring (1 Point)
- Indoor air quality best management practices - outdoor air delivery monitoring (1 Point)
- Performance measurement - system-level metering (2 Points)

On the next page is the full data for the existing buildings in the sample set:

Intervention	# of Points	# of Buildings to Get Credit	% of Buildings to Get Credit
Optimize energy efficiency performance	18	28	100.0%
Existing building commissioning - investigation and analysis	2	28	100.0%
Existing building commissioning - implementation	2	27	96.4%
Existing building commissioning - ongoing commissioning	2	22	78.6%
Performance measurement - building automation system	1	20	71.4%
Performance measurement - system-level metering	2	12	42.9%
On-site and off-site renewable energy	6	23	82.1%
Enhanced refrigerant management	1	14	50.0%
Emissions reduction reporting	1	27	96.4%
Indoor air quality best management practices - indoor air quality management program	1	24	85.7%
Indoor air quality best management practices - outdoor air delivery monitoring	1	11	39.3%
Indoor air quality best management practices - increased ventilation	1	16	57.1%
Indoor air quality best management practices - reduce particulates in air distribution	1	25	89.3%
Indoor air quality best management practices - indoor air quality management for facility additions and alterations	1	21	75.0%
Occupant comfort - occupant survey	1	22	78.6%
Controllability of systems - lighting	1	24	85.7%
Occupant comfort - thermal comfort monitoring	1	10	35.7%
Daylight and views	1	18	64.3%
Green cleaning - high performance green cleaning program	1	28	100.0%
Green cleaning - custodial effectiveness assessment	1	28	100.0%
Green cleaning - purchase of sustainable cleaning products and materials	1	28	100.0%
Green cleaning - sustainable cleaning equipment	1	26	92.9%
Green cleaning - indoor chemical and pollutant source control	1	24	85.7%
Green cleaning - indoor integrated pest management	1	26	92.9%
Innovation in operations	4	28	100.0%
LEED Accredited Professional	1	27	96.4%
Documenting sustainable building cost impacts	1	23	82.1%
Sustainable purchasing - ongoing consumables	1	20	71.4%
Sustainable purchasing - electric-powered equipment	1	23	82.1%
Sustainable purchasing - furniture	1	24	85.7%
Sustainable purchasing - facility alterations and additions	1	11	39.3%
Sustainable purchasing - reduced mercury in lamps	1	28	100.0%
Sustainable purchasing - food	1	6	21.4%
Solid waste management - waste stream audit	1	28	100.0%
Solid waste management - ongoing consumables	1	27	96.4%
Solid waste management - durable goods	1	26	92.9%
Solid waste management - facility alterations and additions	1	16	57.1%
LEED certified design and construction	4	16	57.1%
Building exterior and hardscape management plan	1	27	96.4%
Integrated pest management, erosion control, and landscape management plan	1	24	85.7%
Alternative commuting transportation	15	28	100.0%
Site development - protect or restore open habitat	1	11	39.3%
Stormwater quantity control	1	11	39.3%
Heat island effect - nonroof	1	18	64.3%
Heat island effect - roof	1	22	78.6%
Light pollution reduction	1	22	78.6%
Water performance measurement	2	28	100.0%
Additional indoor plumbing fixture and fitting efficiency	5	28	100.0%
Water efficient landscaping	5	22	78.6%
Cooling tower water management	2	20	71.4%

Table 9: LEED Existing Building Credits – GBIG Sample Set

So what can we learn from all this data and analysis above? What makes LEED buildings different from net-zero or net-zero ready buildings? Looking at the credit categories in both the LEED New Construction data and the LEED Existing Buildings data compared to the interventions in Part II and the individual building case studies in Part III, it seems that the focus of LEED is significantly different from net-zero energy and water development. The focus is more on broad sustainability categories, including air quality, environmental impact of materials, energy, and water use, instead of intense focus on reaching certain tangible energy and water use goals, like net-zero.

Secondly, many credits do not call for a specific performance. Where the goal of net-zero development is clear and right in the definition, to capture as much energy and water as you use, the goals associated with LEED levels are focused on scoring points and a tangible outcome is less concretely defined. Almost every credit that was earned by less than 50% of the sample set was worth 1 point, meaning developers did not see it as important because it was not worth enough points for them to consider. Developers seem to focus more on getting the points than on the overall performance of the building at completion. One of the biggest problems is that certification is awarded based on projections, and not actual performance of the buildings. In a study of Navy-owned buildings, 4 of 11 LEED-certified buildings actually used more energy than their non-certified counterparts.²⁶⁹

Thirdly, there is less focus on water efficiency and treatment. Very few of the existing buildings addressed stormwater management, less than 40% of the sample size. That lack of attention allows large amounts of runoff to be handled by the municipal systems. Only 35% of the new buildings addressed wastewater treatment technologies, again leaving the task to municipal systems.

An article by USA Today based on the analysis of 7,100 LEED-certified or better buildings pointed out a number of flaws with the rating system. First, the analysis showed that developers target the easiest and cheapest points by using common building materials, giving occupants light switches, views of the outdoors, and desk fans. Buildings can earn points using steel and concrete because they are considered recycled materials. They also give points for unproven practices, like giving priority parking spaces to alternative-fueled cars and posting educational displays in public areas of the building. Hotels even get points for the sign in the bathroom that says to reuse your towels. On the other hand, at the time of the analysis, only 14% of the buildings were generating renewable energy on-site and only 12% were including major water-reduction steps like waterless urinals or treatment of waste at the property.²⁷⁰

The statistic that drives home the point and outlines the difference between LEED and net-zero development is the fact that not all net-zero buildings are LEED-certified. In fact, as of 2014, less than 50% (15 of 32) of North America's net-zero buildings had any LEED certification.²⁷¹ That statistic can be misleading, because nothing requires buildings to seek certification and there are other rating systems out there. However, another interesting point is reflected in the certification level of the 15 net-zero buildings that do have LEED credentials. Not all reached the Platinum level. Some are only certified at the Gold level, which starts at just 60 of 110 points. So, one can infer that a higher LEED score does not actually equate to more energy efficiency or a better chance of becoming net-zero.

²⁶⁹ <http://www.usatoday.com/story/news/nation/2012/10/24/green-building-leed-certification/1650517/>, July 24, 2016.

²⁷⁰ <http://www.usatoday.com/story/news/nation/2012/10/24/green-building-leed-certification/1650517/>, July 24, 2016.

²⁷¹ <http://www.usgbc.org/articles/half-us-energy-neutral-buildings-also-show-leadership-leed>, July 24, 2016.

The following chart drives home the difference between LEED and net-zero. This chart represents the top 10 highest scoring LEED New Construction buildings from the data provided. Notice the amount of energy that is created on-site to offset the energy use of the building for the buildings in which information was available, in the farthest right column.

Building #	LEED Score	Asset Type	Building Construction	Energy Outcomes	Water Outcomes	Rainwater Capture	% Energy from Renewables
Building #8	95	Office	Redev.	51% more energy efficient than median EUI for building type	77% reduction of regulated potable water	Yes	71%
Building #10	92	Office	Redev.	55% more energy efficient than similar buildigns	N/A	Yes	N/A
Building #9	92	Office	Redev.	77% more efficient than national benchmark	70% reduction of regulated potable water	No	8%
Building #4	91	Office/Lab	New	N/A	35% reduction in water usage	Yes	27%
Building #15	88	Retail	Redev.	N/A	40% reduction in internal water usage	No	N/A
Building #3	86	Office	New	25% more energy efficient	N/A	No	20%
Building #6	86	Office	Redev. + Addition	Annual energy savings of 51% over baseline code	N/A	No	0%
Building #40	86	Manufacturing	New	N/A	N/A	Yes	50%
Building #25	86	Office	New	50% more efficient than similar buildings	N/A	Yes	0%
Building #26	86	Mixed-Use	New	N/A	N/A	Yes	N/A
							25%

Table 10: Top 10 LEED New Construction Buildings & Their Energy Performance

The average amount of energy that is created to offset building energy use is only 25%. Each of these buildings has a long way to go until it reaches net-zero energy. Also, notice that these buildings are listed in descending order of LEED score. The metrics for water and energy outcomes do not correspond with that order, and do not create a pattern where a lower score means a lower energy efficiency, or vice versa. The ninth building (Building 25) in the order is approximately as energy efficient as the first building. In terms of water, only 6 out of 10 of these buildings are capturing rainwater.

This proves the different foci of net zero development and LEED certification. Performance is the only thing that is important to net-zero projects and achieving that benchmark is highly coveted. For LEED, the achievement is the level of certification and the actual performance of the building is of secondary concern, especially since energy and water use is based on simulations and not actual performance.

Part V: Discussion & Conclusion

Net-zero buildings, even net-positive buildings, are feasible within the built environment. Feasibility takes integrated design driven by site-specific details in order to accomplish net-zero consumption. These projects require forward thinking design teams and a design-build process that brings diverse stakeholders across the development and investment space together: subcontractors, contractors, engineers, architects, the developer, and owners require substantial coordination from day one. In this way, the team can work together to achieve consumption goals based on integrated human capital across the industry. Widespread adoption of these buildings remains an issue – only 39 exist in the United States – as there is lack of widespread technical knowledge – human capital – throughout the development industry to make these types of buildings commercially scalable. The principal finding of this thesis is that the cost, regulatory environment, and attitudes of decision makers may be prohibiting the proliferation of net-zero design interventions and technology solutions for buildings thus far.

LEED buildings are the standard in the United States today, but from a technological and design perspective they demonstrate evidence of limitations with respect to sustainability. There are a number of LEED interventions that are widely accepted and deployed within the built environment including: energy performance optimization, green or cool roofs, encouraging commuting alternatives, highest indoor air quality, sustainable purchasing, recycled materials, and waste management. However, the standard does not reach a net-zero impact with respect to water, and evidence documented in this thesis finds that the top 42 Platinum buildings fall short of net-zero energy performance standards. LEED certification also relies on measurements from simulated performance instead of actual operational performance at full occupancy, which could lead to misleading building performance results. Lastly, the LEED standard also undervalues the use and treatment of water at the building level, which in the future will be a highly valuable resource. Out of the five main categories of LEED scoring, totaling 100 points, only 10 points are allocated to water efficiency.

There is a substantial technology gap in achieving net-zero status within the built environment on a meaningful scale. For the top 10 LEED Platinum buildings, expected energy consumption was decreased by approximately 52% on average compared to “similar” buildings. On the other hand, the Bullitt Center, our model for technological feasibility in this thesis, cut energy consumption by 86.6% compared to the building stock of Seattle, 75.4% compared to the City of Seattle Energy Code, and 63.4% compared to LEED Platinum building certification standards. The design and system interventions represented in this structure are almost 65% more energy-efficient than LEED Platinum standards. Importantly, this gap provides evidence for how the real estate development industry can move toward a “technologically feasible” standard of energy-efficiency.

In addition to cutting energy consumption, these top 10 Platinum buildings are receiving 25% of their energy from renewable sources on average. However, this small sample suggests that the average is based on a wide variety of results. Some buildings are using no renewable energy sources at all, while the best in the set is using 71%, and no institutionally invested buildings have reached net-zero energy. In contrast, the Bullitt Center was supplying 160% of the energy it needed in the year it was monitored for Living Building Challenge certification.

Lastly, only six in ten of these institutionally-owned buildings are collecting rainwater and only 12% of all LEED buildings in the data obtained by USA Today were taking steps to significantly reduce water or treat water on site.²⁷² Water continues to be an inexpensive resource in the U.S. while fuel has been a pain point since the 1970's, but as the view on water as a valuable resource changes, the built environment may adapt to this new value proposition. For new buildings that will have a life-span long enough to face the issues of water scarcity, these developments may need to take on the challenges of water conservation and reuse now.

We have looked at more than 50 different sustainable interventions. On average, they decrease public grid energy by 65% or more, and would allow for a complete offset of building water and sewer use – conditional upon site and climate. In terms of energy reduction, these solutions are daylighting, cogeneration systems, natural ventilation, high-efficiency glazing, photovoltaic cells, wind turbines, geothermal heat pumps, radiant floor systems, thermal enthalpy wheels, chilled beam systems, green roofs, and energy-efficient plug load uses. In terms of water, the most successful interventions are rainwater collection, pervious pavement, low-flow fixtures, composting toilets, and on-site greywater & wastewater treatment and reuse. To implement these technologies, the built environment needs to have access to Building Information Modeling (BIM) and other software sources that can determine which systems are most energy-efficient for a particular location.²⁷³ Variables like southern exposure, wind direction and speed during various seasons, number of sunny days, annual precipitation and daily temperature fluctuations, all play a role in design and development, and these intricate details can make the difference between an amazing project and a missed opportunity.

For developers to advance, the third-party performance standards need to help guide them through commercially diffusible standards. Rating systems could shift towards a model of ex-post energy building performance. Important factors like air quality, energy use, materials content, and water use are all measurable. Many of the points now achievable under some current rating systems are planning and monitoring credits, which are incremental steps to the end goal. While planning and monitoring is

²⁷² <http://www.usatoday.com/story/news/nation/2012/10/24/green-building-leed-certification/1650517/>, July 25, 2016.

²⁷³ <http://sustainability.autodesk.com/blog/bim-net-zero-building/>, July 22, 2016.

important, they are only the first step toward efficiency. The end result is what needs to be quantified under these rating systems. It is only through graded performance that the results will improve, where developers and building owners are held accountable to the real-world performance of their structures, not the energy models that were created before a shovel hit the dirt. Today, the standard is far from where it needs to be. Some LEED buildings are only marginally better than their traditional counterparts. To create real change, there needs to be a bigger gap between the buildings of the past and what is being put in the ground today. The new standard needs to reward buildings for not only reducing energy and water use, but for alleviating stress on the grid and moving energy creation and water treatment in house. New buildings facilitate the need for power plants and waste water treatment plants that are paid for with tax payer dollars and they use a disproportionate amount of these services. As more buildings are developed, more capacity for energy and water is needed. However, if buildings were to reduce or eliminate these needs, municipalities could avoid contributing additional resources to building them. Buildings need to be rewarded for taking these tasks in house. It has been proven that there are significant inefficiencies with large-scale electricity generation and that on-site cogeneration is nearly twice as efficient. It is also proven that moving water across large distances is energy-intensive, while capturing rainwater uses no energy at all. Treating this resource in house would eliminate the energy used by the sewer systems to pump water to and from treatment facilities. These solutions are what is needed to get to the next threshold of sustainability, beyond what is commercially available today in terms of efficient heating, cooling, and lighting systems.

For meaningful strides to take place, policies need to change. One of the issues seen in Seattle was the prohibitive regulatory environment. Regulations with respect to water systems prohibited some of the most important interventions and forced the team to pursue changes to policies, laws, and regulations. Specifically, the entire greywater and wastewater treatment plan on-site was illegal under the existing framework.²⁷⁴ Regulations at the municipal, state, and federal level have to change to facilitate the changing sustainable landscape, which can extend development timelines. Policy programs like the Living Building Pilot Program in Seattle are a great way to test the usefulness and success of these buildings without drastic overhaul. This program allowed for more flexible regulations that stimulated innovative development for up to ten buildings in the city.

Another issue is the current reliance on LEED by many cities across the United States as the final word on building sustainability. Developers garner tax breaks and expedited permitting processes in exchange for certification. However, we have seen that these buildings, without significant changes to the certification process and requirements, are not the future of energy-efficiency and full-scale sustainability based on what is technologically feasible today. Cities need to take the lead and push actual performance

²⁷⁴ Thomas, 40-41.

and reward projects for sustainable interventions like renewable energy sources and on-site water capture and treatment.

In the same vein, developers are accountable for affecting this change as well. The latest research shows that developers and building owners are earning a 13% premium on buildings labeled as green compared to similar buildings not built to sustainable levels.²⁷⁵ However, developers are failing to implement the most costly technologies that deliver the greatest reduction in municipal burdens, like cogeneration systems (9% of U.S. building supply) and on-site wastewater treatment. There needs to be a better balance between immediate profits and long-run financial sustainability, whether that is through policy change, financial valuation model disruption, or other means. What we do as developers is important, and developers across the globe have added unquantifiable value to the world in which we live. But developers have also contributed to the energy-thirsty built environment that exists today.

To further the understanding of net-zero development, more research is needed into how these sustainable interventions interact with one another. There are a number of different combinations of systems, design, and materials that work together to create energy-efficient projects. A centralized source of how these all work together in different climates around the world would be helpful to developers looking to build sustainable buildings. A database of outcomes from real-world examples could push the net-zero movement forward. One of the hardest parts of net-zero achievement is the time and research it takes to develop the best plan of action for a specific site. If general rules of thumb existed, development timelines could be shortened while still increasing the sustainability and performance of future projects. In addition to research on new buildings, renovation strategy research is important. Many say that the most sustainable buildings are the ones that already exist. The ability to reuse structures eliminates the need for new materials and the energy used to put them in place. Sustainable solutions for existing, yet energy-obsolete buildings is important to the future of sustainability. Lastly, further research into the importance of water and the implications of waste water treatment at the municipal level versus the building level can help create a narrative for change in regulatory environments as well as public perception. Water is going to become a highly important resource and we as developers need to be ahead of the curve when that time comes.

Although we still have progress to make, we are getting there. We have proven that net-zero and net-positive development is possible, and there is a growing trend to pursue this distinction. In 2015, there were 152 “emerging zero energy buildings” in the United States according to the New Buildings Institute.²⁷⁶ These buildings either have a publicly stated goal of net-zero energy, are in the planning, design or construction phase, or have been operating for less than a year and do not have sufficient data to support verification. That number is nearly four times the number of net-zero buildings that existed as of the same

²⁷⁵ Eichholtz, et. al, 2013.

²⁷⁶ <https://newbuildings.org/wp-content/uploads/2015/11/2015ZNEbuildingsList1.pdf>, July 26, 2016.

time, signaling a massive step forward. In addition, we have curtailed per capita energy use and are using less energy today than we were in the 1970's, even given the vast increase in energy-reliant technology and devices with which we are equipped. The future of net-zero and net-positive energy and water development is at our fingertips. The technology exists, the skills of developers and design teams exist. The thinking still lags behind, but that is something that can be fixed. In the end, it is important to keep in mind the big picture of sustainability, to be as mindful of our impact as we can while still creating amazing places in which people can thrive, be it socially, commercially, or otherwise.

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