



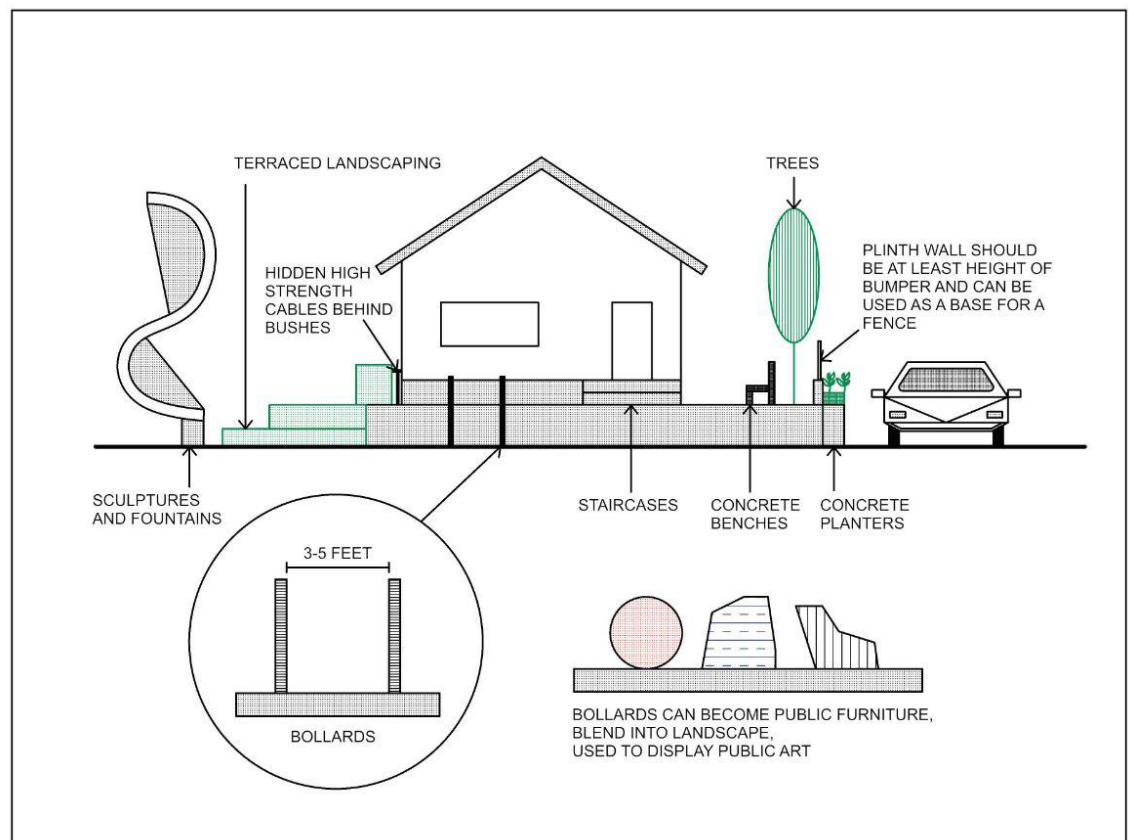
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Pattern Language for a More Resilient Future

Helen Hoang, Othniel Williams, and Annette Stumpf

October 2023



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Pattern Language for a More Resilient Future

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Abstract

The Department of the Army (DA) manages over twelve million acres of land for military use, and almost 138,000 buildings. Military installations and other US DoD operations contain architectural structures and civil infrastructure that require continuous improvements to resiliency. This includes resiliency in the form of protection against both natural and man-made disasters.

This document seeks to identify multiple risks to infrastructure and people and encourages open dialogue for creative solutions. Designers and engineers as well as other disciplines can work together to achieve higher resiliency in both new and renovated work. The following sections are created to provide a starting guide, utilizing various tools to discover the best resilient design strategies for your building. This special report will argue for actionable design strategies; drawing inspiration from historical building forms, while also looking toward emerging technologies that should be further explored.

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Preface

This study was conducted by the US Army Engineer Research and Development Center (ERDC) for the Office of the Deputy Chief of Staff (DCS), G-9 under Project 09LF9B, “FY2020 Support for the US Army Sustainable Design and Development Policy to Ensure Facilities are Resilient, Efficient, and Affordable.” The technical monitor was Ms. Brandy O. Reed, Energy and Facilities Engineering Division, (DAIN-ODF), Operations Directorate, Office of the Deputy Chief of Staff (DCS), G9 (Installations).

This study was a virtual collaboration between two architect interns from Sacramento District Corps of Engineers CESPK and researchers at the US Army Engineer Research and Development Center Construction Engineering Research Laboratory (CERL). Ms. Helen Hoag and Mr. Othniel Williams did a rotation with ERDC-CERL focusing on resilience and sustainability of Military Construction. CESPK funded Helen and Othniel’s effort. CERL researchers who participated in this effort included Ms. Julie L. Webster, Mr. Samuel Stidwell IV, Ms. Allison R. Young, and Ms. Annette L. Stumpf, who lead the collaboration.

Special thanks to Mr. Matthew Valentine (CESPK) for encouraging Helen and Othniel to spend their rotation at ERDC-CERL.

The work was performed by the Installation Readiness Branch of the Infrastructure, Science, and Engineering Division, ERDC-CERL. At the time of publication, Mr. Chuck Schroeder was branch chief; Mr. Tim Shelton was division chief; and Dr. Justin Berman, was the technical director for Infrastructure, Science, and Engineering. The deputy director of ERDC-CERL was Ms. Michelle Hanson, and the director was Dr. Andrew Nelson.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

The building industry has a large environmental impact and carbon footprint. It is also heavily embedded into our everyday lives—people exist, eat, play, sleep, and seek protection inside buildings. Resiliency must be thought as a responsibility not only to the environment, but also for the future of mankind. According to the Whole Building Design Guide (WBDG) Sustainable Committee (2021),

buildings use 36% of America's overall annual energy consumption, and 65% of the electricity demand. Furthermore, buildings account for 30% of the total carbon dioxide (CO₂¹, which is the primary greenhouse gas associated with atmospheric warming), 49% of the sulfur dioxide, and 25% of the nitrogen oxides emitted in the US.

Additionally, the estimated value of construction spending in the United States in 2017, as a ratio of the construction spending to GDP, stood [at around 6.36%](#) (Statista 2018). Thus, a large part of the US economy relies on the building industry. Physical buildings themselves, which are stores, factories, schools, office buildings, and emergency services are also inter-related to economic resilience.

In recent years, massive natural disasters, such as wildfires, hurricanes, floods, pandemics, terrorism, and increasing demand for energy are challenging the way things are built.

Architecture has historically been designed according to geographical location or site. In the new age of designing for resilience, designers must return to thinking outside the (air-conditioned, energy intensive) box.

1. For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Buildings should be designed to be resilient to both current and anticipated problems. Questions to consider are,

- How will local policies, codes, and laws impact the enactment of design strategies?
- Will the upfront cost of technologies used for resilient design be profitable in immeasurable ways? Consider manpower retention, mental health, and continuity of operation.

1.2 Objectives

The objective of this work is to communicate resilient design principles to designers and engineers. This could be thought of in many ways, such as legislation, theoretical approaches, and through past and proven methods. However, this document will focus on visual and systematic techniques that are of interest, especially to people dealing with vertical infrastructure.

When discussing resiliency, the first thought is about new technologies that can be implemented. This intuitively makes sense because designers often look toward innovation to solve future problems. However, actionable specifics of building design are often neglected; designers should look back to historical design techniques that were used. Throughout the centuries, people have explored various techniques to solve problems that humanity has always faced, and will continue facing—that is, our environment, meteorological disasters, and man-made challenges. It is through the combination of both historical and future technologies building designs can become more resilient to impending challenges.

When discussing the features of a resistant building, the most important question to ask is: resistant to what? This report seeks to be an overview of the various challenges in designing a resilient building. It is by no means comprehensive of all the intricacies and nuances in this challenge, but it hopes to simplify the overwhelming web of concerns faced today. This document seeks to identify multiple risks to infrastructure and manpower and encourages open dialogue for creative solutions. Designers and engineers as well as other disciplines can work together to achieve higher resiliency in both new and renovated work.

1.3 Approach

As the Department of the Army (DA) interns from the Architectural Design Section, rotating through Construction Engineering Research Laboratory (CERL), we initially held meetings to discuss the meaning of resiliency. Through a series of presentations on various resiliency topics, we began to understand the multifaceted aspects in the problems, but also the complexity in solutions.

We took a look at the DoD Climate Assessment Tool (DCAT). It was created to analyze and estimate climatic risks at specific DoD military installations in 2050 and in 2085. The impacts looked at wildfire, drought, coastal flooding, riverine flooding, heat, energy demand, historical extreme conditions (hurricanes and ice jams), and land degradation (erosion). We also looked at the NOAA that maps billion-dollar weather and climate disaster's historical data across the US. It also mapped out drought, flooding, freeze, severe storms, tropical cyclones, wildfire, and winter storms. We realized that resiliency should be looked at from both a historical and future-focused perspective and broken down per topic to be more digestible.

Hoping to simplify and organize the web of ideas, we initially tried to create a spreadsheet that would help designers identify the most pressing issues facing a building in relation to climate zones. We understood that there was no single correct answer—sacrifices must be made in different aspects of a building in order to prioritize the highest risks. However, as the list grew longer and increasingly too simplistic, we realized an illustrated report would be more encompassing of the research we compiled during this summer at CERL.

1.4 Scope

This work focuses on building and site design techniques that may be considered experimental but also draws inspiration from historical DoD research and applied design on military installations. Effort was exerted to allow room for discussion on the benefits of both historical and innovative techniques.

2 Defining Resilient Design

2.1 Definitions

2.1.1 Resiliency

The Resilient Design Institute (June 2021) states that *resiliency* is not a single solution, nor an objective perspective. It is problem solving that [“balances proactivity and reactivity to inform solutions to disruptions.”](#)

According to the US Army Corps of Engineers (USACE) EP 1100-1-5 *USACE Guide to Resilience Practices* (2020), the concept of resiliency is broken down into four elements: prepare, absorb, recover, and adapt.

2.1.2 Prepare

The definition of being prepared is to protect against threats and provide *preventative* measures to shield from damage to life, health, property, and ecosystem. Developing short-term and emergency and long-term plans, training, and identifying threats are good ways to prepare. Questions to consider for preparedness are,

1. What are the current threats of different areas being built in?
2. What are the unique conditions of the areas to consider?

2.1.3 Absorb

The definition of absorb is the ability to take the punch, increase *durability*, and the ability to withstand. Questions to consider for durability are,

1. What materials are the most durable per weather and other challenges?
2. How can buildings allow for more human resilience?

2.1.4 Recover

To recover is to be able to *return to the previous state* of functionality. Re-opening as soon as possible and to allow for less damage in future events; easy to fix. Questions to consider for recovery are,

1. What is recovery in terms of a humanistic approach (such as post-Covid-19 protocols? Daylighting?)
2. How can designs allow for aid during emergencies? How can infrastructure be changed to allow for quick recovery?

2.1.5 Adapt

Modifying a solution to address the disruption of new conditions or creating new solutions entirely are ways to adapt. *Flexibility* during times of change is critical, as is the ability to recover functionality without prior infrastructure. It is best to consider designs that allow for adaptation. Questions to consider for adaptability are,

1. How can buildings be designed to function in “the new normal”, where people, the world, and things are altered forever?
2. How can building program types be easily translated to another?

2.2 Resources

Resilient Design Institute:

<https://www.resilientdesign.org/resilient-design-strategies/>.

DoD Climate Assessment Tool (DCAT)—Analyze risks in Climate Zones and DoD military installations: <https://dodclimate.sec.usace.army.mil/ords/f?p=118:1.>²

Continental United States, Alaska, and Hawai'i installations:

<https://dodclimate.sec.usace.army.mil/>.³

Rest of the world installations DCAT;

https://dodclimate.sec.usace.army.mil/dcat_row.⁴

Leadership in Energy and Environmental Design (LEED®) pilot credits for resiliency:

<https://www.usgbc.org/articles/revised-leed-resilient-design-pilot-credits-now-available.>

2. CUI—Military Personnel Access only.

3. CUI—Military Personnel Access only.

4. CUI—Military Personnel Access only.

2.2.1 LEED Assessment and Planning for Resilience (IPpc98)

- “Determine potential vulnerabilities at the project location.
- Risks include sea level rise, extreme heat and more intense winter storms.
- To earn the credit, project teams must identify risks related to the effects of climate change” (Blackwelder 2019).

2.2.2 LEED Designing for Enhanced Resilience (IPpc99)

- “Risk-related information collected as mandated by credit IPpc98 with mitigation.
- Project teams must address either one or two of the top hazards, with one point available for each topic.
- Allows teams to earn acknowledgement for mitigating multiple risks” (Blackwelder 2019).

2.2.3 LEED Passive Survivability and Back-Up Power During Disruptions (IPpc100)

- “Centers around the concept that buildings should be able to safely shelter occupants during a power outage
- Provide backup power.
- Addressed access to potable water as an option for compliance” (Blackwelder 2019).

2.3 RELi resilience rating system

<https://www.usgbc.org/articles/unveiling-reli-20-piloting-new-standard-resilience>.

[RELi is a rating system](#) adopted by the US Green Building Council (USGBC); it is similar to LEED with requisites and credits leading to certification levels. RELi’s eight categories are,

1. Panoramic Approach (planning, discovery, and systems thinking)
2. Hazard Preparedness
3. Hazard Adaptation
4. Community Vitality
5. Productivity, Health, and Diversity
6. Energy, Water, and Food
7. Materials and Artifacts
8. Applied Creativity (innovation).

2.4 Precedents for RELi

Some projects that piloted RELi or aspects of it are provided in the following sections.

2.4.1 Christus Spohn Shoreline Hospital—Corpus Christi, Texas

The hospital is equipped with a five-day emergency generator capacity, a minimum of four days of food and water storage, redundancy in the central plant, an emergency plan, and facilities for community outreach and engagement. The building focuses on resilience against hurricanes. It was [built to be above the 500-year flood plain](#), with hurricane-resistant technology (Logan 2018). The area underneath the ambulance canopy can become a mass-decontamination facility in case of an oil rig or industrial disaster—implementing flexibility.

Accounting for social factors, resilient design was also designing the emergency department to provide for two flows of traffic. Patients who are injured because of civil unrest or gang-related violence can wait in separate areas, preventing disasters from human conflict. This shows that resilient circulation design anticipates both natural disasters, disease control, pandemics, and social factors.

2.4.2 University of Oklahoma Medical Center—Oklahoma City, Oklahoma

The building was constructed with the threat of tornadoes in mind. While it also incorporated a five-day emergency generator capacity, four days of food and water storage, and redundancy in the central plant, [the building was tailored to concerns of Oklahoma City, Oklahoma; tornadoes](#) (Logan 2019). The building's skin was designed with steel-stud spacing that was reduced to 9 inches, fiberglass reinforcing mesh under the terracotta rain-screen, and impact resistant glazing. There is also a green roof to protect the building from wind-driven projectiles and a radiant heating system under the exterior walkways and driveways to reduce the hazard of snowy winter storms. The building's foundation and steel frame was also reinforced with moment frames to withstand potential earthquakes.

2.4.3 Bell Museum of Natural History University of Minnesota—St. Paul, Minnesota

Perkins & Will designed the [Bell Museum](#) with biodiversity resilience as priority (2018). The glazing is fritted with tightly spaced narrow gray lines

to prevent bird striking on glass. The building envelope uses certified thermally modified wood, certified to Forest Stewardship Council criteria, to address the sustainability of wooden materials in building design. The landscape design contains an irrigation bioswale, as well as a pond which can accommodate a 1,000 year rainfall. It was also designed to ensure that the water levels will never fall below a minimum required for the local habitat, aiding with bird migration and preserving the ecosystem.

2.5 Whole Building Design Guide (WBDG) and USACE Public Works Technical Bulletins

The Whole Building Design Guide is a portal containing a large collection of federal facility criteria, design recommendations, project management suggestions, continuing education materials and additional resources. The WBDG federal facility criteria section is an extensive library containing the most current DoD, Army, and other federal agency construction criteria. Resources available on the WBDG will help project development teams design and build high performance sustainable buildings as required by policy.

DoD Unified Facilities Criteria Program resources are found here:

<https://www.wbdg.org/ffc/dod>.

Tri-Services Sustainability Program content is found here:

<https://www.wbdg.org/ffc/dod/tri-services-sustainability-program>.

Army Corps of Engineers engineering and design publications are available here: <https://www.wbdg.org/ffc/army-coe>.

USACE PWTBs are informative bulletins that help installation personnel deal with all types of environmental issues found at installations. See

https://www.wbdg.org/ffc/army-coe/public-works-technical-bulletins-pwtb?order=field_date&sort=asc&page=1.

2.6 Sustainability versus resilience

Sustainability and resilience often have overlapping elements. For the sake of clarity, this document will differentiate these two topics that are often grouped together as shown in Table 1.

Table 1. Differences between sustainability and resilience.

Resilience	Shared Similarities	Sustainability
• Multiple Energy Sources • Multiple Water Sources • Disaster Fortitude Design • Emphasis on Passive Systems • Reduced Environmental Effects • Flood Plain Evaluation of Building Location	• Energy Independence • Water Independence • Renewable Resources • Resource Storage • Environmental Effects • Community Support	• Energy Reduction • Renewable Energy Production • Recycled/Reclaimed Water • Locally Sourced Material • Community Responsibility • Access to Transportation • Indoor Environmental Quality • Brownfield Restoration

2.7 Topics

The following topics contain actionable building techniques that can be implemented. Each geographical location may be more susceptible to certain risks. Some precedents are included as examples how people have previously solved these issues and implemented some of these design techniques.

1. Drought
2. Flood
3. Tropical Cyclones
4. Tornadoes
5. Fire
6. Air Quality
7. Energy
8. Waste
9. Antiterrorism

3 Drought

The first civilizations were formed along rivers, emphasizing the importance of water to human existence. Hence, a water shortage becomes a problem in a world where demand has gone up, and supply has gone down.

Droughts are caused by a lack of precipitation, over a long period of time, resulting in a shortage of water necessary for agriculture and depleting surface and groundwater supplies. According to the Natural Resources Defense Council, [“developing nations are particularly vulnerable to the impacts of climate change and drought,”](#) as it creates economic toll, worsens water and food insecurity, impacts mass migrations, and exacerbates problems such as famine and civil unrest (Denchak 2018).

Projected weather impacts show that droughts will become increasingly prominent across the nation. In fact, droughts have been a great concern in the western part of the United States for a long time. This weather event causes [“substantial damage to agriculture, affects domestic water supply, energy production, public health, and wildlife; and contributes to wildfire” \(NDMC 2023\).](#) Drought is the second-most costly form of natural disasters behind hurricanes; between 2012 to 2016, low levels of rainfall and record-breaking heat created [California’s worst drought in 1,200 years \(Chou 2015\).](#)

3.1 Resources

US Drought Monitor—droughts in real-time, updated:

<https://droughtmonitor.unl.edu/>.

USGS Drought Map—droughts in real-time, updated:

https://waterwatch.usgs.gov/index.php?id=ww_drought.

National Integrated Drought Information System—monitor and outlook:

<https://www.drought.gov/>.

NOAA Mapping Billion-Dollar Weather and Climate Disasters—find areas in US most affected:

<https://www.ncdc.noaa.gov/billions/mapping/freq/1980-2021>.

3.2 Techniques

3.2.1 Water towers and rain barrels

Depending on anticipated precipitation, harvesting rainwater could provide for necessary redundancy in cases of emergencies or assist with the municipal water system. Cisterns used for water storage has been a technology that was implemented in the past. Building these water storages in a way that allows for gravity to feed into the building could be a great passive way to ensure water is available. See Section 3.4.1, *Water towers—New York City, New York*, as precedent.

3.2.2 Hydrophones

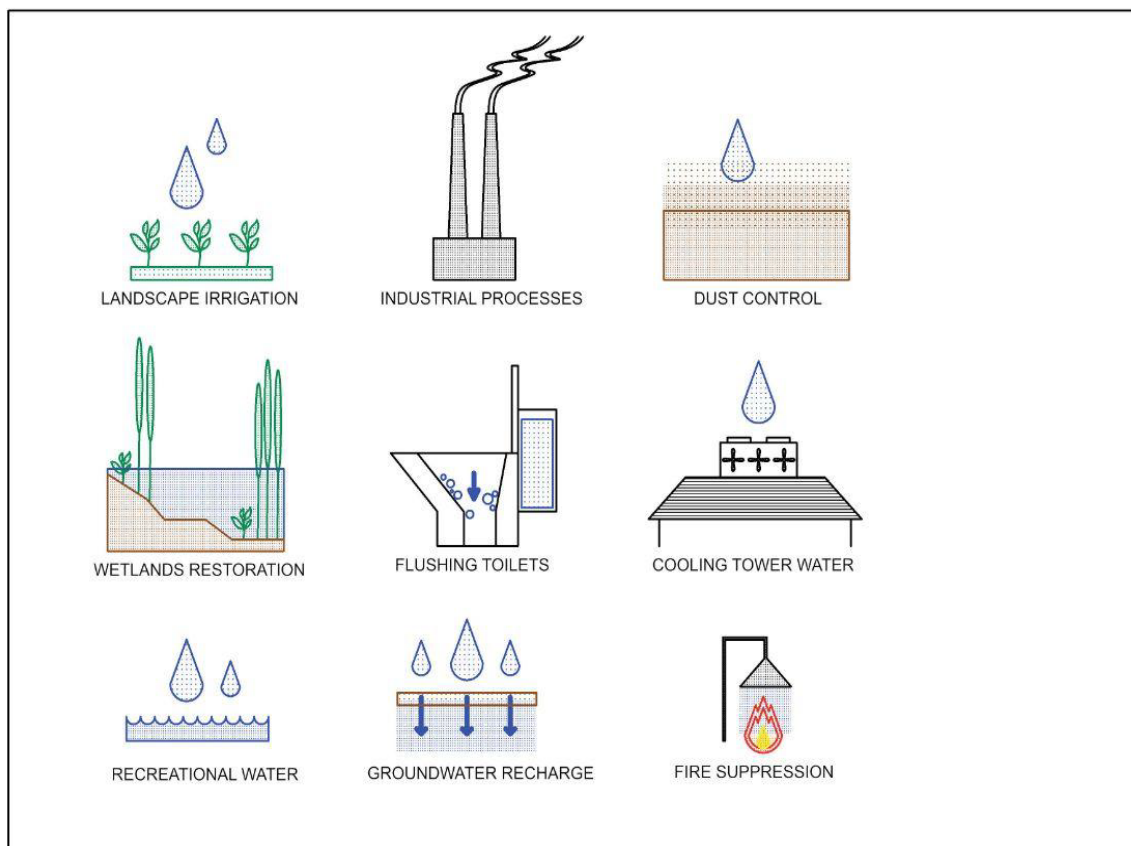
Hydrophones are acoustic devices that listen continuously for the minutest of leaks along the pipeline. Las Vegas, Nevada, has implemented hydrophones along the main strip. There are [13 EchoShore®-TX hydrophones](#) along the transmission main, pinpointing locations and notifying engineers at Southern Nevada Water Authority to alert them of needed maintenance (Echologics 2023). See Section 3.4.4, *Water recycling and conservation in casino resorts in Las Vegas—Las Vegas, Nevada* precedent for more information on how Las Vegas, Nevada, handles solutions for the shortage of potable water.

3.2.3 Recycled water and filtration systems

There are many uses of [recycled water](#) that can be used in place of potable water (Cucamonga Valley Water District, n.d.). While it cannot be used for drinking, it has several other valuable uses, including the following:

- Landscape Irrigation
- Fire Suppression
- Industrial Processes
- Dust Control on Construction Sites
- Wetlands Restoration
- Toilet Flushing
- Cooling Tower Makeup Water
- Groundwater Recharge
- Recreational Water Bodies

See Figure 1 for a visual representation of potential uses for recycled water.

Figure 1. Uses for recycled water.⁵

USES FOR RECYCLED WATER

3.3 Low flush toilets

Toilets account for nearly 30% of an average home's indoor water consumption. The [federal EPA standard](#) for toilet water use is 1.6 gallons per flush. Low flow models use about 20% less water, at 1.28 gallons per flush. Dual flush models that utilize 1.6 gallons for solid waste and 0.8 gallons for liquid waste offer water savings of roughly 30%.

Although the installations of low flow fixtures are more expensive, the up-front costs can usually be recovered within the first year with utility savings. Replacing inefficient toilets with WaterSense labeled models could save a household more than \$140 per year in water costs, and \$2,900 over the lifetime of the toilets (EPA 2022).

5. All images were created by the authors of this report.

Additionally, consider [composting toilets \(NutriCycle Systems, n.d.\)](#). It is a great off-grid option that conserves both water and waste. Read more about composting toilets in Section 10 *Waste*, of this report for more details and Section 3.4.2 *Bullitt Center—Seattle, Washington* precedent.

3.3.1 Smart water cisterns

Smart water cisterns allow for real-time monitoring sensors and controls that can detect when rain is expected. With data, it can predict how much rain will fall and estimate the capacity of the tank. Then, it can determine how much water needs to be released into the rain garden, which recharges the aquifers underground. [Tetra Tech](#) (2022) is one of the companies that explored this technology.

3.3.2 Rethinking landscaping

Plants that are drought resistant and native are best for water efficiency. Green lawns must be rethought, especially in areas that do not receive much precipitation. Additionally, pervious landscaping designs that limit water runoff could be beneficial in recharging the local groundwater. According to the [Center for Landscape and Urban Horticulture](#) (UCANR 2023),

replacing a lawn with a mix of trees, shrubs, ground-covers, vines, and herbaceous perennial plants that creates a nearly complete, well-performing plant canopy over the landscape can be expected to have 50% less water demand than a cool-season lawn or at least 30% less than a warm-season lawn, assuming the lawn was watered to perform well and the new planting is well-designed with a highly efficient and well-managed irrigation system.

See section 3.4.4 *Water recycling and conservation in casino resorts in Las Vegas—Las Vegas, Nevada* precedent on how Las Vegas, Nevada, restricts the creation of new front lawns and rewards citizens for replacing front lawns with low-water options.

3.3.3 Parking design and pavements

[Paving systems](#) can be designed to allow rainwater to seep down and be temporarily stored at the bottom of the paving layer, slowing absorption

into ground, help recharge groundwater supplies and reduce runoff (City of Lincoln Nebraska 2023).

Pollutants are often carried in runoff water when finding its way to natural rivers and lakes. Parking lots paved with pervious surfaces also helps with breaking down pollutants, water vegetation, recharge groundwater, and reduce stormwater runoff.

3.3.3.1 Pervious concrete

Pervious concrete is comprised of the following:

- Is a mixture of hydraulic cement, coarse aggregate, water, and admixtures with little to no sand.
- Contains only enough paste to bind aggregate together, not enough to fill in space between the aggregates; with 17%–25% void space.
- Is suitable for parking, pathways, and driveways.

3.3.3.1.1 Pervious concrete pavers

Pervious concrete pavers are recommended for the following:

- Systems that contain masonry (bricks and blocks) that have gaps along the sides. The gaps are filled with materials like crushed rock that allows the surface water to infiltrate into the ground below
- and can capture a large enough amount of stormwater.

3.3.3.1.2 Pervious grass pavers

Pervious grass pavers should be used for the following:

- In a modular grid that prevents vehicular traffic from compacting soils in the top layer and distribute pressure to a crushed rock base layer.
- So that water can infiltrate the rock layer below.
- The subbase for the pavers should have a rock layer and some soil mixed in to help grass growth.
- To reduce the heat island effect.

Other water management techniques such as bioswales, vegetated roof, and stormwater practices can prevent erosion and allow for groundwater

replenishing. See Section 3.4.3 *Merrill Center—Chesapeake Bay, Virginia* precedent for how their parking design facilitated surface runoff.

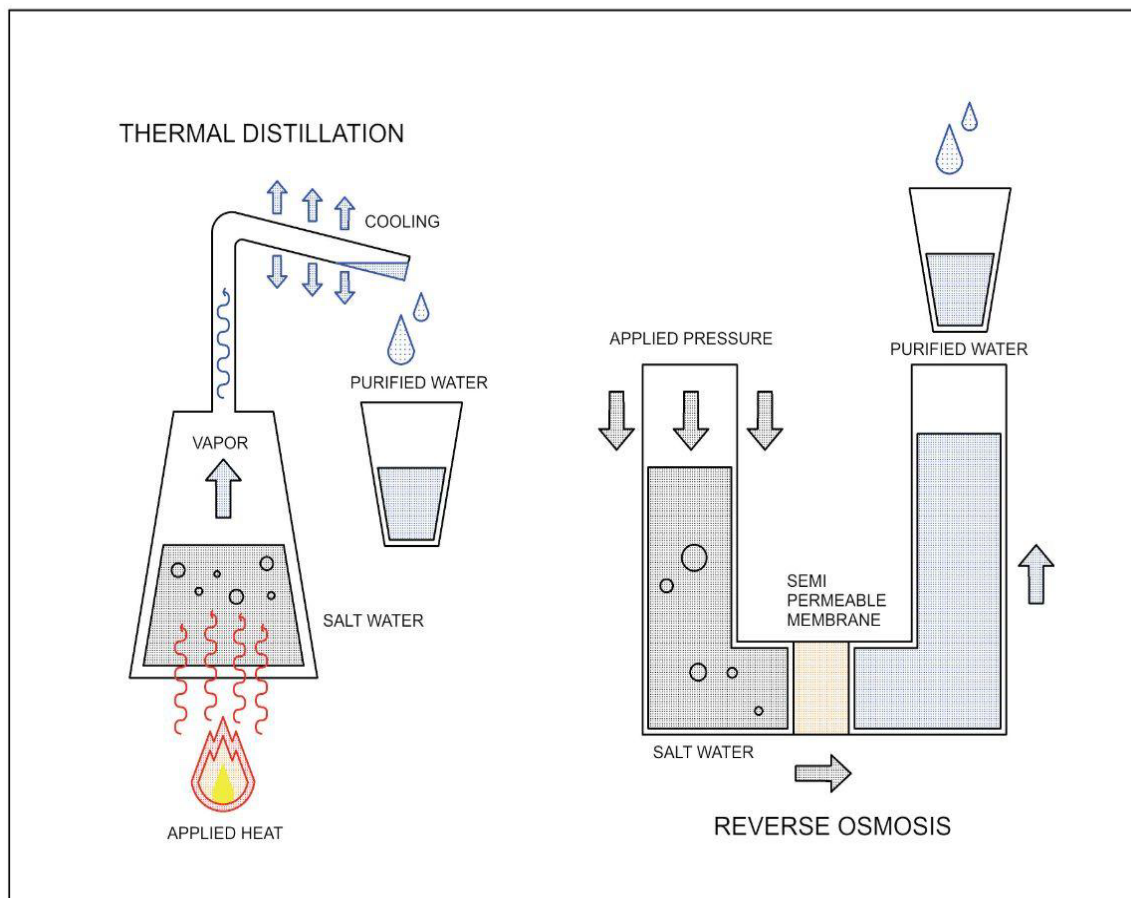
3.3.4 Desalination efforts

[Desalination](#) is expensive and energy intensive (Ramirez 2019). However, it is important to think about it in terms of resilience. The most common desalination methods are thermal distillation, in which water is heated until the pure vapor separates from the salt and other components, and reverse osmosis, where high amounts of pressure push water through a filter to separate it from salt.

According to the International Desalination Association, there are 20,516 desalination plants across 150 different countries, providing water to 300 million people.

According to Ramirez (2019), “the biggest existing facilities are Saudi Arabia’s [Ras Al Khair](#), which uses both thermal distillation and reverse osmosis, and [Israel’s Sorek](#), hailed as the largest and cheapest reverse osmosis plant in the world when it opened in 2015. The Middle East is the dominant region in the world when it comes to desalination (unsurprising given its hot climate and oceanside locale); the West’s largest plant is located near [San Diego and produces 50 million gallons of fresh water per day](#).” See Figure 2 for a diagrammatic explanation between thermal distillation and reverse osmosis.

Figure 2. Desalination techniques of thermal distillation and reverse osmosis explained.



DESALINATION

3.3.4.1 Solar desalination

Solar thermal power is promising for small scale desalination efforts for offgrid systems.

3.3.4.2 Graphene

This material is made of carbon atoms arranged in a hexagonal lattice, which have been praised for its strength and conductivity. It is difficult to manufacture but holds lots of promise for water filtration.

However, according to [an article published from Yale](#) (Robbins 2019), “it takes two gallons of seawater to make a gallon of fresh water, which means the gallon left behind is briny. It is disposed of by returning it to the ocean and—if not done properly by diffusing it over large areas—can deplete the ocean of oxygen and have negative impacts on sea life.” The brine

produced from wastewater can be a source of pollution and have consequences in the ecosystem. It is important to note the negative impacts when discussing resilience.

3.3.5 Atmospheric water harvesting

The [technology for harvesting water from the atmosphere](#) has been used in drought-struck regions, for disaster relief in areas of water contamination, in military operations, and at remote resorts with limited fresh water supplies (Notman 2020).

3.3.5.1 Fog net harvesters

Huge nets for harvesting water from fog are implemented in the Atacama and Namib deserts. The existence of water scarcity and lots of fog makes the location perfect for this technology. Liqiu Wang at the University of Hong Kong has been trying out nets that mimic the pattern of spider webs and Tak-Sing Wong at Pennsylvania State University in the US has been inspired by the design of pitcher plants and rice leaves (Notman 2020).

Designs inspired by biological forms could serve to harvest water in drought-stricken areas. Incorporating that into architecture could be multi-functional and add an additional layer of water resilience into the building.

3.3.5.2 Condensation against cool coils

The majority of atmospheric water harvesting implements the technique of passing cool air through a cool coil, in which water from the air condenses. The coil is coated with a food-grade coating to prevent metal contamination and the air pushed through the coil is filtered.

3.3.5.3 Desiccant-based

Desiccants have lower energy consumption and high water extraction efficiency. This technology involves hygroscopic materials that suck up water like a sponge. An example of desiccant based technology are silica gel sachets.

3.3.6 Direct potable reuse

[Direct Potable Reuse](#) (DPR), is a technology that delivers purified wastewater to customer's faucets without an environmental buffer—such

as aquifer or river (Udasin 2021). Aside from battling regulatory and permitting challenges, cities also need to help people overcome the *yuck factor*, changing public perception of what clean water means. *Toilet-to-tap* still means that the water is drinking-water quality. Public acceptance of DPR could improve water resilience in cities.

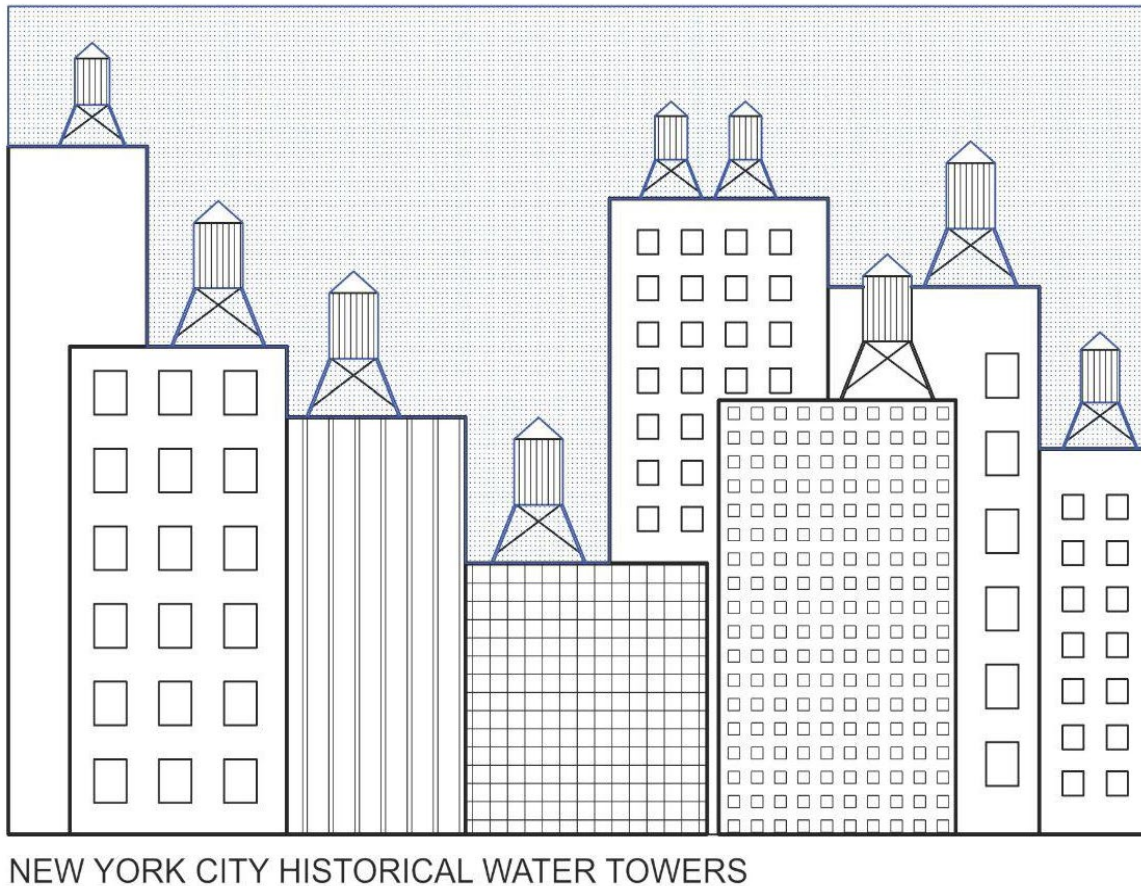
3.4 Precedents

3.4.1 Water towers—New York City, New York

During the 1880s, indoor plumbing began replacing well-drawn water, and fifty years later, New York City started implementing [water storage tanks](#) (Gannon 2022). The local water pressure was too weak to raise water to the upper levels, so they were placed on roofs, and buildings that were six or more stories were equipped with an additional water pump. About 5,000 to 10,000 gallons of water are stored in these wooden tanks. The upper layer was for everyday use, while the bottom was reserved for emergencies.

Water tanks last roughly 30 to 35 years, can be built within 24 hours, and take just two or three hours to fill with water using an electric pump. Wood is also better at moderating temperature than steel tanks. They cost roughly \$30,000 to build; a steel tank would cost roughly four times the amount. Another great thing about wooden tanks is that water stored in them does not freeze in the winter and stays cool during the summer months. See Figure 3.

Figure 3. New York City historical water towers were once a part of the city skyline.

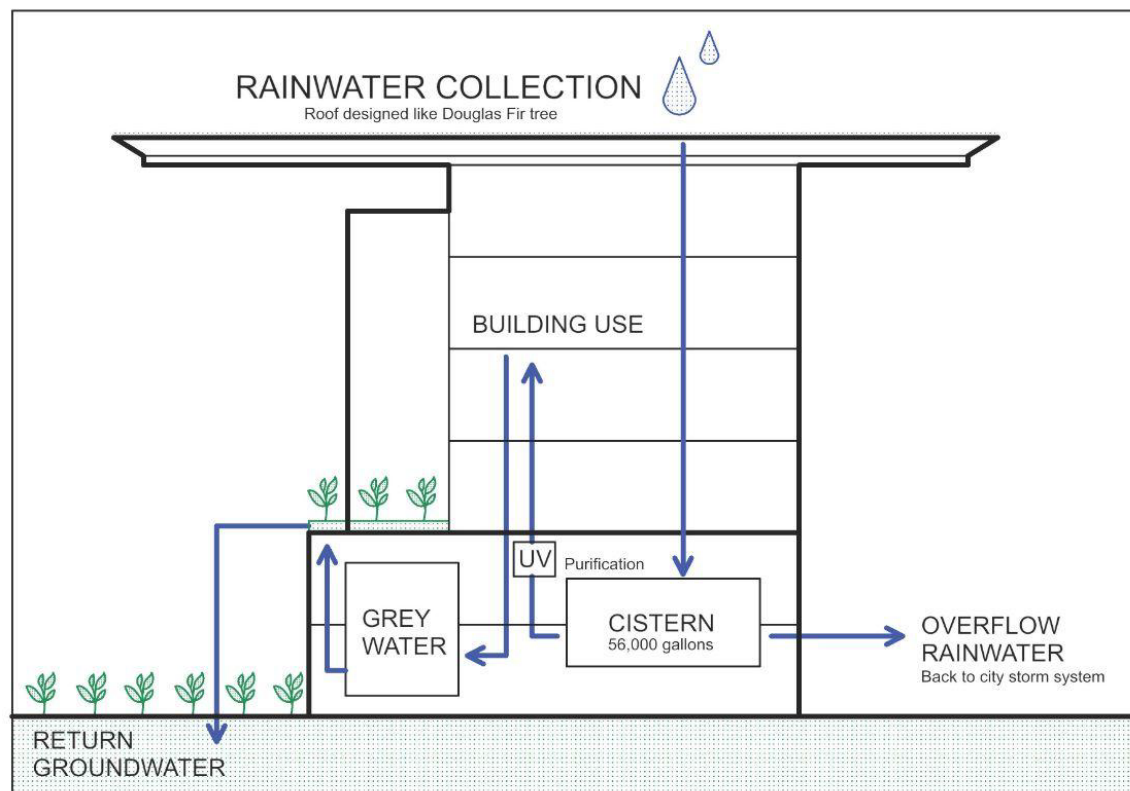


Designers can look toward the past to revive these icons of water resiliency. They become prominent design elements that are embraced by the local community and celebrated, normalizing the culture of resiliency.

3.4.2 Bullitt Center—Seattle, Washington

The roof of the Bullitt Center was [designed like a Douglas fir tree](#), capturing water and returning water to the soil and atmosphere (Bullitt Center 2013). Rainwater is collected and stored in the concrete cistern, which is filtered for building. The rainwater is filtered through three ceramic filters and passed under a UV light with activated charcoal and a small amount of chlorine. Next to the cistern is a *day-use* tank that holds gallons of clean, potable water. See Figure 4.

Figure 4. Bullitt Center water system explained.

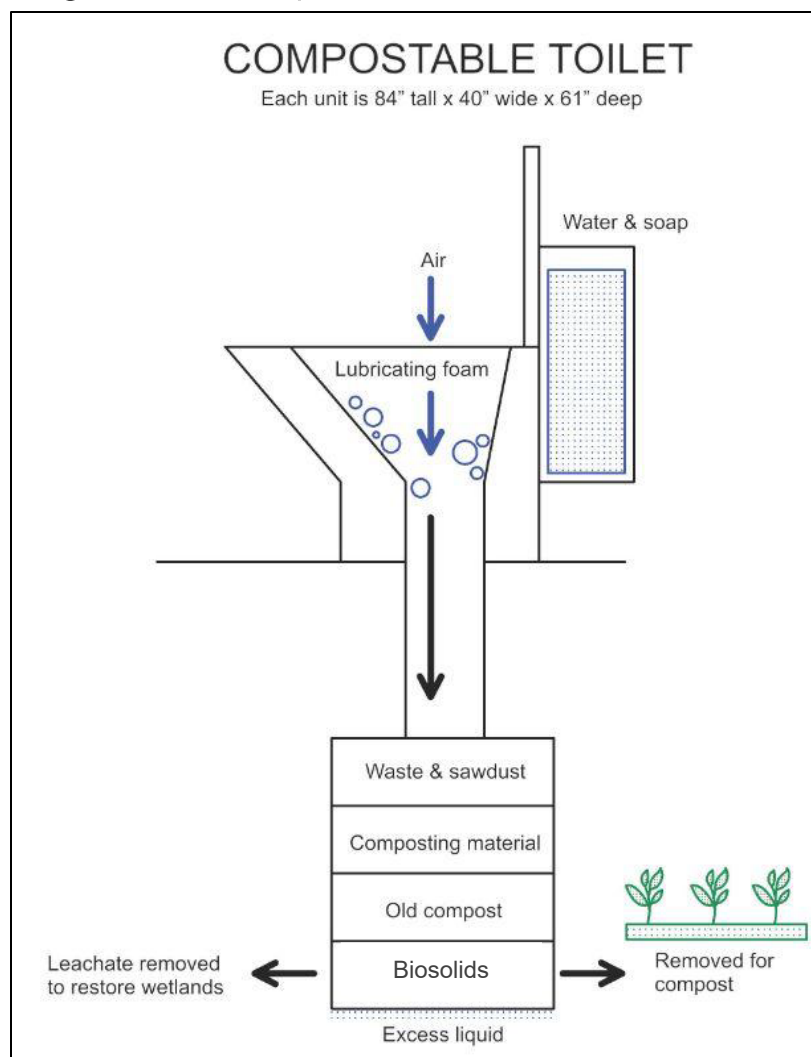


BULLITT CENTER

The building's [greywater treatment system](#) is stored in a 500 gallon storage tank and then pumped to the third floor constructed wetland (Bullitt 2013). This wetland is a green roof that is filled with gravel and soil, and horsetail is the primary plant used. The water is filtered with this plant and released in the bioswale on the western edge of the site. The water is then filtered down the 20 feet of gravel before percolating into the water table.

Another unique building feature are the [composting toilets](#) (Bullitt 2013). Human waste is transferred directly from the waterless toilet into a composter that is periodically taken offsite to be used as fertilizer. The Phoenix Composting Systems are each about the size of a Volkswagen Beetle (84 in. tall × 40 in. wide × 61 in. deep). The decomposition process is aerobic, eliminating the release of methane gas and dangerous odors. See Figure 5.

Figure 5. How the compostable toilet from the Bullitt Center works.



3.4.3 Merrill Center—Chesapeake Bay, Virginia

The building is an [ENERGY STAR® “Top Performance” building](#) with a rating of 98 for energy efficiency (CBF 2023). Based on the average use of energy of similar office buildings, this is an annual savings of \$50,000. It is equipped with 111 kW⁶ PV (photovoltaic) panels that generate 135 MWh of electricity each year.

The four year average water savings equals 1.35 million gallons of water not processed by a sewage treatment plant. The building also implements

6. For a full list of the spelled-out forms of the units of measure used in this document, please refer to US Government Publishing Office Style Manual, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMAN-UAL-2016/pdf>.

the use of solar water heaters for the onsite showers and bathrooms. The water savings is 80% less than a conventional building, and that includes both the onsite laundry facilities and showers. The average daily water use is 150 gallons, and 40% of that is rainwater collected onsite. Rainwater is stored in the three large water cisterns that are a celebrated architectural element at the front of the building. Without all these water saving technologies, the building's daily normal use would be estimated to be about 1,000 gallons each day.

Additionally, the Merrill Center is also equipped with composting toilets that saves the client money on water and sewage costs. It was \$25,000 to install, and is predicted to have a payback of less than ten years.

The parking was designed to reduce harmful runoff, placing the parking lot underneath the building and using gravel that could slow runoff and allow particles to drop off. The building siting was also done in a way to disturb the site as little as possible; the wetlands and surrounding native habitat were restored, and cutting down as few trees as possible. The center now has a more permeable surface than before.

3.4.4 Water recycling and conservation in casino resorts in Las Vegas—Las Vegas, Nevada

Despite the facade of lavish water use along main casino resorts in Las Vegas, Nevada, they actually consume [only 7.6%](#) of water in Southern Nevada (Person 2015). Sixty percent of water is used by single and multifamily households; 70% of that is for landscaping.

There are several creative solutions implemented by the casino resorts as a solution to a shortage of potable water. The [Venetian Resort](#) utilizes *nuisance water* from the shallow aquifer only 20 feet below the surface (CDP 2021). Usually nuisance water requires purification for use. The Venetian Resort built a water treatment facility at the bottom level of the Palazzo parking garage. The purified “nuisance water” is used for watering plants, cleaning trucks, and for the cooling tower. The assistant chief of Las Vegas Sands Facilities Department, Jim Albers, said that the treated water is actually better than municipal water (Sands 2018). The Venetian also upgraded their pool and spa filters with glass filters, saving 6 million gallons of water per year.

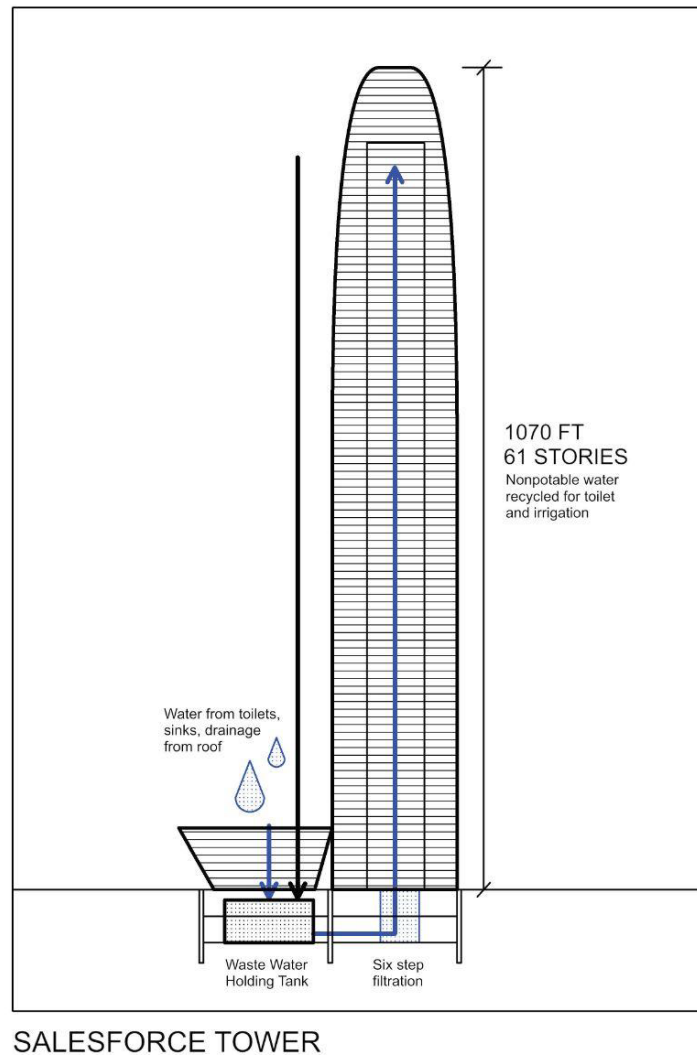
The city of Las Vegas, Nevada also implemented rigorous water conservation efforts for years by [banning new front lawns](#) (Goldman 2016). They also recycled 40% of all indoor water consumed into treated water, re-turned to Lake Mead.

3.4.5 Salesforce Tower—San Francisco, California

Known as the [largest commercial building with black water recycling system in the United States](#), the Salesforce tower boasts 7.8 million gallons of drinking water saved every year (Cooke 2018). The tower is 1,070 feet tall, (62 stories). The blackwater recycling system will take water from any of the building's sources, including from toilets, sinks, and drainage from the roof. It is housed in the basement; the wastewater holding tank is renovated to fit in between two levels of a handful of parking spaces underground. The treated blackwater will be used to irrigate plants and to flush toilets. This translates to a 76% reduction in the building's overall water demand, and 30,000 gallons of water every day. See Figure 6.

The saved water could go [to the local community](#), and to farmers in the central valley, aiding with the extreme drought in California (Salvin 2019). Additionally, there is a [long-term payback](#) with the expected rising cost of water over time (Sisson 2021). Developers also see the value in blackwater systems for irrigation and cooling towers at this scale. See Figure 6.

Figure 6. Salesforce Tower black water recycling system.



3.4.6 Solaire—New York City, New York

The [Solaire is a high rise](#) for 700 residents living in New York City, New York (Epstein 2008). With all the water-saving features implemented, the building had reduced indoor potable water use by 43%. The building's on-site wastewater treatment facility processes 30,000 gallons of black water per day, reusing the recycled water for cooling towers and flushing toilets. Additionally, the rooftop garden has a stormwater retention system, a mat below the soil's surface. Rainwater, spilling over into the drains of the roof, is collected in a 10,000 gallon tank, located in the building's basement. The rainwater is used for drip-irrigation. Additionally, low flow toilets and ENERGY STAR dish and clothes washers are installed (Epstein 2008).

3.4.7 Fort Huachuca Water Conservation Plan—Arizona

US Army's Fort Huachuca has implemented water saving policies that have helped with the problem of water scarcity in the area. Since 2010, [Fort Huachuca](#) has reduced groundwater pumping by 60% through projects such as installing turf on training fields, waterless urinals, installation of water-efficient irrigation, and harvesting rainwater for irrigation (Caprioli 2010). Receiving around 15 inches of rain per year, [Fort Huachuca looks toward rainwater harvesting](#), as 80% of the water needed at a military installation does not require potable drinking water (DA 2021). This includes vehicle wash stations, construction, irrigation, and cooling towers.

In [residential housing](#), water-saving showerheads, waterless fixtures, and front loading washers also helped reduce water intake (UA 2023). The Mountain View golf course was converted to a desert course, and the irrigation system was upgraded to reuse treated effluent.

The community management plan also includes metering of water to identify locations of heavy use, and for detection of water leaks and waste.

3.4.8 Fort Bragg Community Emergency Services Station—North Carolina

The [Community Emergency Services Station](#) in Fort Bragg, is the first Army Military Construction project awarded with LEED Platinum certification (USGBC 2012). Aside from the plentiful amount of daylighting beneficial to employee retention and wellness, the building also boasts a large reduction in potable water usage. The water collected off the roof is used to wash fire trucks and rescue vehicles. The project utilizes bioretention cells in its stormwater management design that uses plants and soils for the removal of 85% of pollutants from stormwater runoff. The landscape uses native plants that do not require irrigation beyond natural rain events, saving the installation both money and potable water. The building also implemented high efficiency fixtures to reduce water usage.

4 Flood

Flooding occurs when there is an [“overflow of water that submerges land that is usually dry”](#) (Earth Networks, n.d.) They are the most common severe weather event, as there are many reasons for flooding.

- Riverine flooding
 - This occurs when water levels rise above the top levels of rivers and stream banks. This phenomenon [happens](#) because of excessive rain from a tropical storm, persistent thunderstorms, combined result from rainfall and snowmelt, and when ice accumulates behind river bends, causing overflow (Earth Networks, n.d.). [Ice jams](#) occur in colder regions in late winter and early spring (Earth Networks 2017).
- Coastal flooding
 - This occurs along the coast of the sea. It is usually caused by a combination of sea tidal surges, high winds, and barometric pressure. [Storm surges](#) come from tropical cyclones, tsunamis and higher than average tidal waves (Earth Networks, n.d.). They usually are accompanied by high winds, low atmospheric pressure, and higher waves. Coastal flooding can be very dangerous, as it causes inundation very quickly.
- Inland flooding
 - This occurs usually in urban settings; flash floods, the number one severe weather killer in the United States, are a type of [inland flood](#) (Earth Networks, n.d.). With possible flood heights over 30 feet, flash floods can cause great damage to infrastructure and loss of lives. This type of flooding is usually caused by heavy rains or extended steady rainfall for stretches of time. Snowmelt can also cause inland floods. Additionally, inundation in urban areas could be caused because of problems with the city sewage infrastructure, broken dams, or ice jams.

Rising sea levels, rapid urbanization and development without planning for water runoff, less permeable surfaces in cities, less greenspace for storm water runoff, and increasing number of storms and natural disasters

are all factors that contribute to flooding. It is important to design buildings that will be resilient to this danger; refer to Section 4.1 *Resources* to analyze the flooding risks a location has.

4.1 Resources

USGS WaterWatch—real time flood information:

https://waterwatch.usgs.gov/?id=ww_flood

FEMA Estimated Base Flood Elevation—flood analysis per location:

<https://webapps.usgs.gov/infrm/estBFE/>

FEMA Flood Map Risk—flood risk per location:

<https://msc.fema.gov/portal/home>

NOAA Mapping Billion-Dollar Weather and Climate Disasters—disaster and risk mapping:

<https://www.ncdc.noaa.gov/billions/mapping/freq/1980-2021>

4.2 Techniques

4.2.1 Elevate above flood level

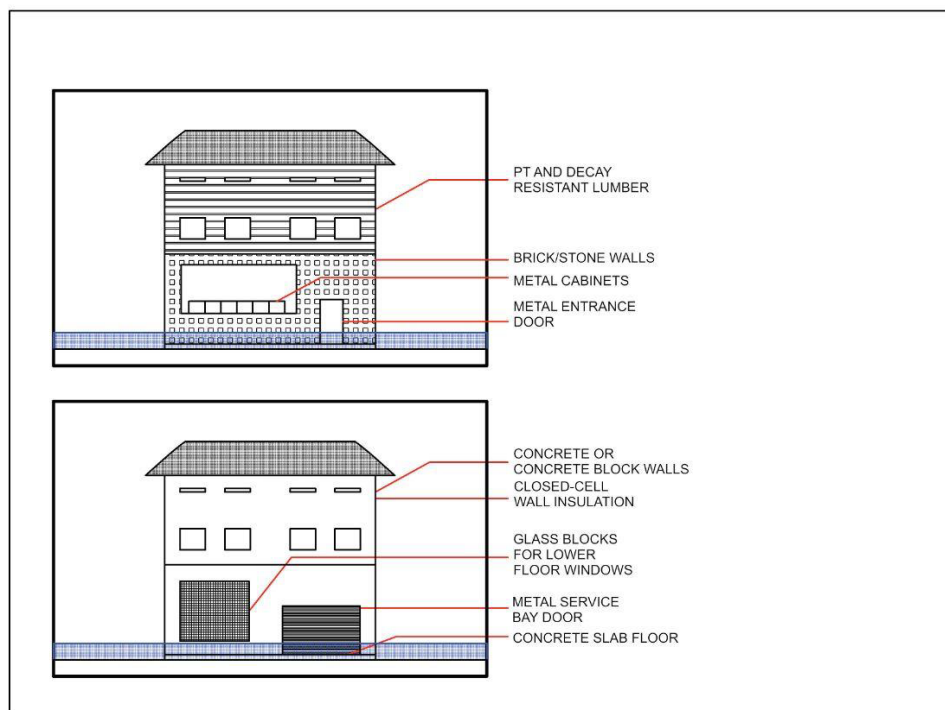
The flood level elevation for specific areas can be found online using programs such as the [Estimated Base Flood Elevation Viewer](#) run by FEMA (n.d.).

4.2.2 Use flood resilient material

Flood water can be both hydrostatic (standing water) and hydrodynamic (flowing water), and in most cases will result in displaced foundation walls, collapsed structures, floating fuel tanks, scouring, and more. To limit the amount of damaged property, utilizing materials that can withstand these conditions would be helpful in resilient design.

[Flood resistant materials](#) are those which can last in contact with flood waters for at least 72 hours without significant damage (Cao 2021). Some materials that are flood resilient are concrete, glazed brick, closed cell and foam insulation, steel hardware, pressure treated and marine grade plywood, ceramic tile, water-resistant glue, polyester epoxy paint, and more. See Figure 7 and Table 2.

Figure 7. Flood resilient materials.



FLOOD RESILIENT MATERIALS

Table 2. [FEMA's list of flood-resilient materials \(2008\).](#)

Flooring Materials	Wall and Ceiling Materials	Other
- Concrete - Concrete tile - Precast concrete latex - Bituminous, ceramic, clay, terrazzo, vinyl rubber sheets - Tiles pressure-treated (PT) - Decay resistant lumber PT wood - Cold-formed steel	- Brick - Metal - Concrete - Concrete block - Porcelain - Slate - Glass block - Stone - Ceramic - Clay tile cement board - Cold-formed steel - Reinforced concrete polyester epoxy paint - PT and decay resistant lumber - PT and marine grade plywood foam - Closed-cell insulation decay resistant wood	- Hollow metal doors - Cabinets - Foam or closed-cell insulation

4.2.2.1 Coatings, sealants, and waterproofing veneer

Applying a coating of sealant on the interior and exterior could help reduce damage when rebuilding.

4.2.2.2 Raise or flood-proof HVAC, plumbing, and electrical

Elevate equipment, such as heating, ventilating, air conditioning, plumbing appliances, plumbing fixtures, duct systems, and electrical equipment including service panels, meters, switches, and outlets.

4.2.2.3 Install foundation vents or sump pumps

Install foundation vents to allow flood water to flow through the home rather than pooling up inside. Sump pumps are a type of equipment that pumps water out of basements where flooding happens regularly. Sump pumps with battery backup are highly recommended during emergencies, as they allow active systems to continue functioning when the power goes out.

4.2.2.4 Anchor fuel tanks

Fuel tanks are easily moved by flood waters, which could drive the tank into walls, damage other property, and cause contamination and further damage. [Anchor recommendations are found here](#) (DOE 2022).

4.2.2.5 Install sewer backflow valves

When sewers flood, it can cause damage that is both difficult to repair and hazardous to occupants' health. Backflow valves will prevent sewage and contaminated water from coming back into the building in a flooding event (FEMA 2021a).

4.2.2.6 Floating buildings

Polystyrene slabs covered in concrete for the base of structure are often used as a building material to allow buildings to float when flooding happens. As water rises, the ground floor moves up with it, up to 5 meters. This type of building is suitable for areas of high flood risk.

Connected to a floating pier, smaller buildings of two stories are the most suitable. Additionally, these buildings can be connected to services using waterproof pipework that is flexible for movement of the building. See

Section 4.3.1 *Floating Farm Poultry—Rotterdam, Netherlands* precedent and Section 4.3.5 *Floating Office Rotterdam—Rotterdam, Netherlands* precedent.

4.2.2.7 Pillars or stilts

This method of design is most suitable for coastal zones, and not as suitable in urban environments. It is commonly seen in the Netherlands. Areas underneath the stilts are harder to manage or use effectively, so they are usually allocated to parking. Additionally, the space underneath could pose a lack of surveillance or security and the lack of light means difficulty growing plants. Benefits to stilts in flood prone areas is to raise the buildings above the flood waters or storm surges. See Section 4.3.6 *Little Island Pier 55—New York City, New York* precedent, Section 4.3.3 *Nissan Stadium—Yokohama, Japan* precedent, and Section 5.3.3 *Sand Palace—Mexico Beach, Florida* precedent.

4.2.2.8 Waterproofing and the “[Sacrificial Ground Basement](#)”

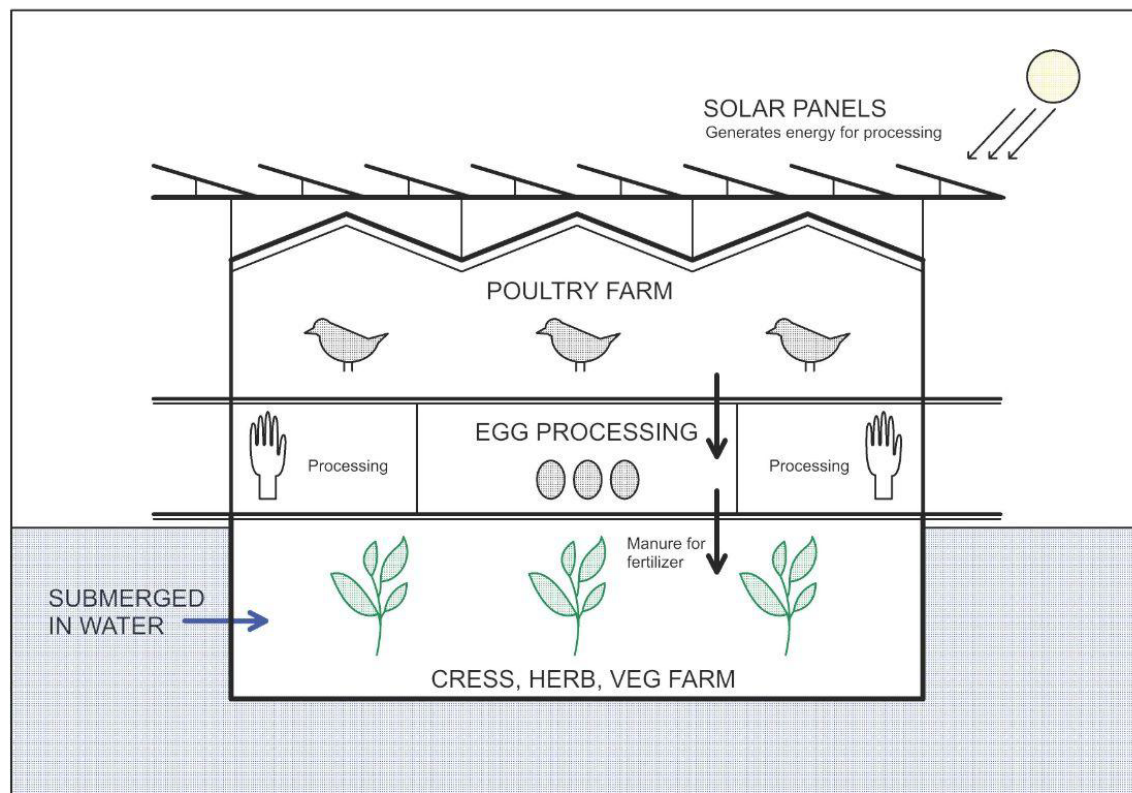
This method of design anticipates the flooding of the ground floor (Pels-makers 2014). This means that the ground floor is programmed with spaces that occupants do not deem necessary (such as parking, storage, or basements), and designed to be durable against flooding. This method is best for areas that have a low to medium probability of flooding. See Section 4.3.2 *Wall House by Creative Architects (CTA)—Bien Hoa, Vietnam* precedent and Section 4.3.3 *Nissan Stadium—Yokohama, Japan* precedent.

4.3 Precedents

4.3.1 Floating Farm Poultry—Rotterdam, Netherlands

The [floating structure](#), designed by Goldsmith, is an urban farm that combines the facilities for 7,000 hens, processing space, and area for farming vegetables, herbs, and watercress (Angelopoulou 2020). See Figure 8.

Figure 8. Floating Farm Poultry simplified into circular waste-to-product system.



FLOATING FARM POULTRY

The roof is equipped with large solar PV panels that collect energy to use for the LED light in the submerged cress farm, and processing equipment. The hens are cared for on the top floor, while the “ground level” is used for processing eggs and the crops grown in the bottom floor. Chicken manure is also dried to become fertilizer granules, used for the farm or sold commercially.

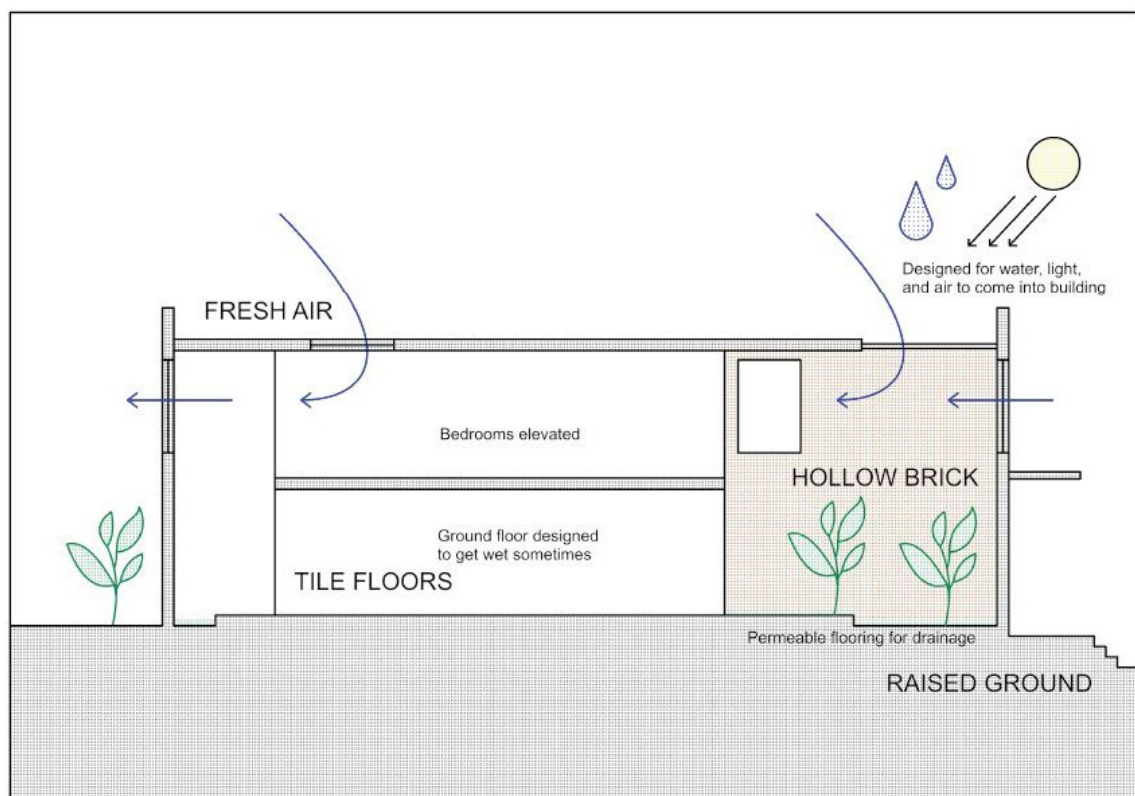
Previously, Goldsmith successfully created a [floating dairy farm](#) with a similar concept (Angelopoulou 2019).

4.3.2 Wall House by Creative Architects (CTA)—Bien Hoa, Vietnam

The main idea of developing this house was one that is able to *breathe* by itself. CTA designed [the two story home](#) to be surrounded by walls of hollow bricks that are lined up in the opposite direction, allowing for fresh air circulation and more natural light (Myers 2020). See Figure 9.

Because it was designed with the intent to let the external elements into the home, the materials used were chosen with intention to be durable and waterproof. Sited near a river, the home was designed with the intention of possible inundation. The ground floor is raised on a higher elevation, and with an internal courtyard that has water-permeable flooring, allowing for water to be absorbed. Additionally, programming was done to ensure that spaces such as the kitchen, and bathroom are located on the ground floor, which are often spaces that are moisture-proofed in Vietnam.

Figure 9. Wall House.



WALL HOUSE

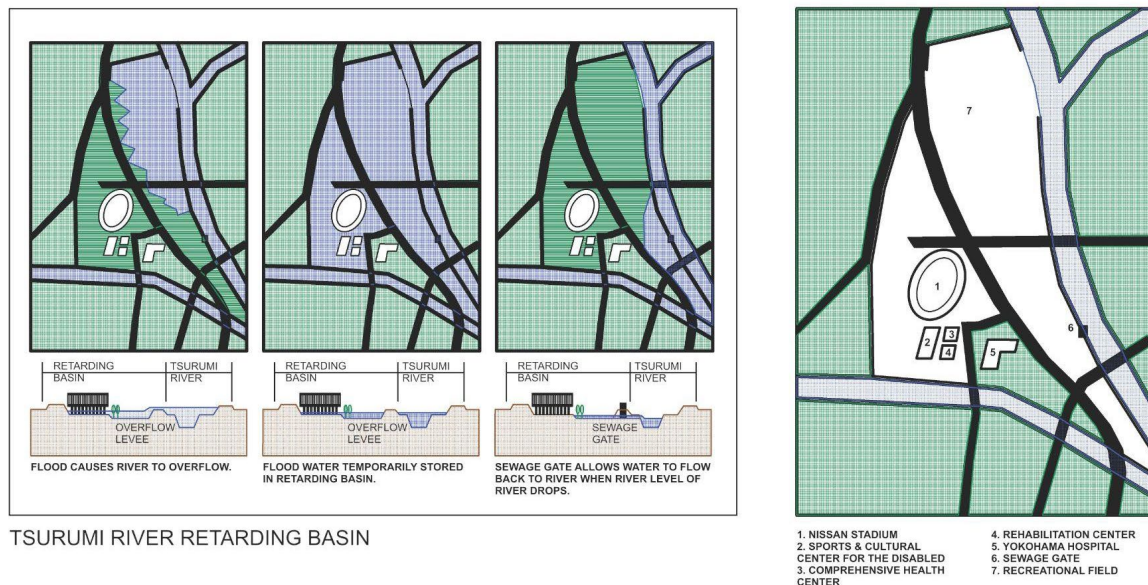
4.3.3 Nissan Stadium—Yokohama, Japan

The Nissan Stadium is built in the [Tsurumi River Basin](#) (Japan River, n.d.). [The entire area](#) also includes a comprehensive health center, a rehabilitation center, a Sports Center for the Disabled, and a tennis court with a recreational field that turns into a water storage reservoir when it rains and the river overflows (Giang and Dat 2020). All these [public facilities](#) are built on a raised elevation to avoid flooding, underneath the natural river overflow into the accretion basin during the monsoon season (Japan River, n.d.).

The Nissan Stadium was also additionally elevated with piers, and designed to accommodate an overflow, when the basement would come into use for water storage, leaving the above facilities unflooded. The basement of the stadium can store water up to 10 meters deep. When it is not flooded, the bottom floor acts as a parking structure. The city also monitors the status and notifies residents in the case of possible inundation, allowing them to move to higher ground.

The [detention basin function of Shin-Yokohama Park](#), in which the Nissan Stadium is located, attracted attention during the passing of Typhoon Number 19 (Hagibis). It showed water draining from the Tsurumi River, filling the park, while the Nissan Stadium stands in the midst of the flood water like an island (Plaza Homes 2019). When it is not flooding, the retarding basin acts as a sports and recreation field. See Figure 10.

Figure 10 Tsurumi River Retarding Basin operating at three stages of river overflow.



4.3.4 Flooding infrastructure in the Netherlands

The Dutch have a long history of managing flooding, because almost half the country is below sea level or less than 3 feet above sea level. [Two thirds of the Netherlands](#) is susceptible to flooding (Wikipedia 2022a).

[Civil Infrastructure](#) (Kraft 2023) was constructed to deal with this issue including dikes, walls to keep water out, along with continuously operating pumps that were [historically windmills](#) (Netherlands, n.d.). The concept of

[“Room for Water”](#) is also implemented, which means letting water take over some land to protect the rest (Iovenko 2018). Additionally, planning ensures that there is enough space for river bends, as well as blocking off sea rise with flood gates and dams.

4.3.5 Floating Office Rotterdam—Rotterdam, Netherlands

Architecture and experimental structures built to be flood resilient are also commonly explored in the Netherlands. The [largest floating office building](#), three stories in height, was constructed entirely of engineered-timber in Rotterdam (World Architecture 2020). The building is held [together with nuts and bolts](#), without any adhesives, meaning that it’s completely demountable and can be reassembled in any other location (PCN 2021). The material of the building also allows for possible reuse.

According to Souza (2021), [“The Floating Office Rotterdam](#), designed by Powerhouse Company, is self-sufficient, generating solar energy and relying on a water-based heat exchange system.” Aside from the ability to adapt to changing sea levels, the building also frees up roof space for solar PV panels, and for vegetation. The base structure of the office is made of concrete, with parts of it using recycled concrete. Dutch concrete that is porous, allows buildings to float. The new homes constructed do not have typical concrete foundations anchoring them to the ground. Instead, they have [air-filled concrete bases](#) (BMC 2019). A similar technology is used for the larger scale office project.

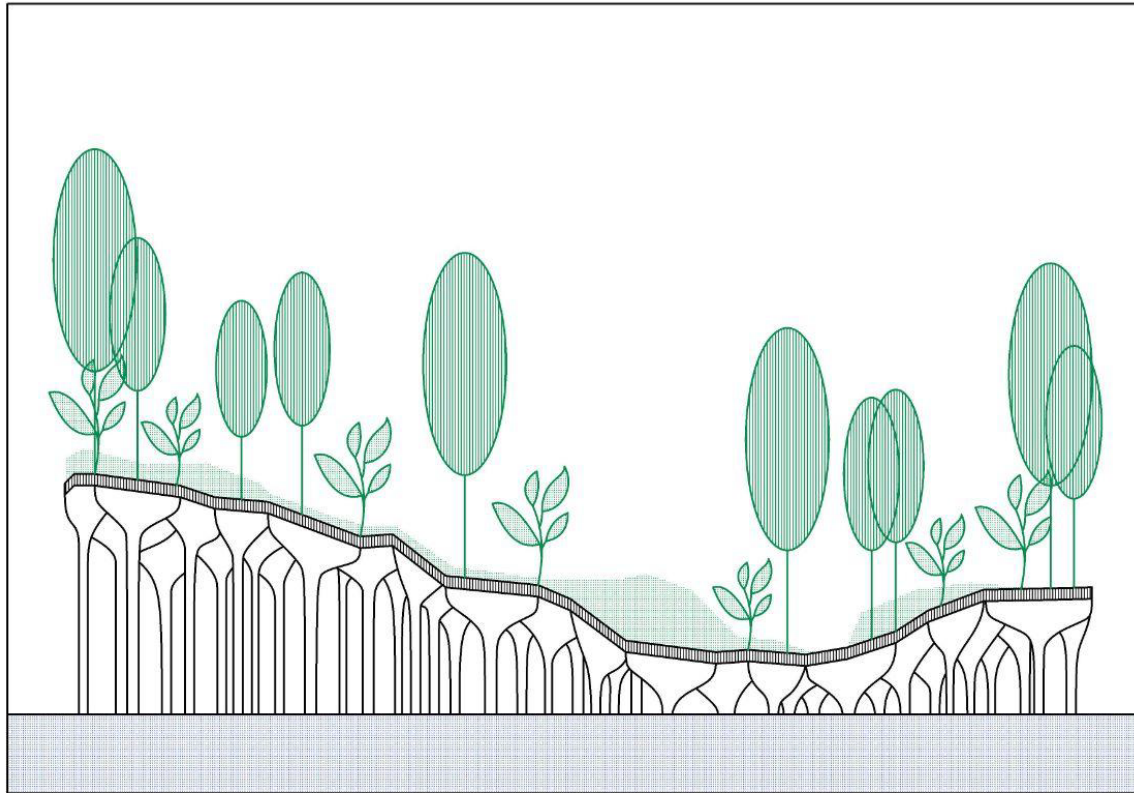
Other forms for floating architecture were explored in the Netherlands. The [floating greenhouse](#) is situated in water retention areas, which was designed to adapt to changing water levels (UGBG, n.d.). Simple, and [small wooden homes are also constructed on stilts](#) nearing river banks to allow for flooding resiliency when the water levels change (Grozdanic 2013).

4.3.6 Little Island Pier 55—New York City, New York

Pier 54 was damaged by Hurricane Sandy in 2010. In response to the damage, the space was [reimagined to become a new type of public space](#), with pier-like design elements, as an homage to the surviving piers after the hurricane (Little Island, n.d.). It is now an island park that people can visit, coupled with a 687-seat amphitheater. The park is landscaped with 35 species of trees and 65 shrubs species. The composition of the [soil was engineered to reduce erosion](#) and other plantings were used to shield the

park from strong winds from the Hudson River (Wikipedia 2022c). See Figure 11.

Figure 11. Pier 55, Little Island honors the historical value of the site while creating public space for residents on the water.



PIER 55, LITTLE ISLAND

4.3.7 Very large floating structures (VLFS) technology

There was some [historical research](#) into very large floating structures (VLFS), mainly by the United States and Japan in the mid-1900s (Suzuki et al. 2006). The Okinawa International Ocean Exhibition in 1975 demonstrated some constructed experiments of large floating architecture, demonstrating the dreams of floating cities and man-made islands. A prototype of the unique floating city called Aquapolis was built at Hiroshima for the exhibition. The concept of a marine city was fundamental to the development of the Metabolist architecture movement in Japan during the 1960s, an optimism toward technology and flexible living.

The United States focused primarily on military applications, such as the [C-130 Hercules Landing in 1963](#) (Leone 2020). The US Navy decided to try and land a Hercules on an aircraft carrier in moderately rough seas 500

miles out in the North Atlantic off the coast of Boston. The Airplane became the largest and heaviest aircraft to ever land on an aircraft carrier. The test successfully completed 21 landings and takeoffs from the USS aircraft carrier (305 meters in length) using no arresting gear or catapult. However, the practicality of a mobile offshore base became too high risk, and the research for mobile offshore bases (MOBs) decreased.

MOBs were supported by the US Navy with a substantial amount of research effort through the 1990s. There were similar concepts envisioned as a rescue base to operate in support for humanitarian relief, potentially in fortifying human resilience.

4.3.7.1 Applications of VLFS

- [MOB \(mobile offshore base\)](#)—several elements maneuvered into position and joined to form a single base, which could support combat operations from a secure position (Wikipedia 2022d)
- Airports—example includes the Kansai International Airport in Japan in 1973
- Offshore Port Facilities
- Offshore Storage and Waste Disposal Facilities
- Energy Islands and Food Production
- Habitats

4.3.8 The Pentagon remote delivery facility (RDF)

The Pentagon was [built in a record time of 16 months](#) (Lange 2019). It was completed in January 1943 with the help of 1,000 architects and 14,000 tradesmen who worked endlessly. The structure was meant for temporary use for WWII, but the military decided to keep it as the command center. It now houses the Office of the Secretary of Defense, the Joint Chiefs of Staff, and the highest echelons of the Army, Navy, Marine Corps, and Air Force.

The [Remote Delivery Facility](#) (RDF) is a shipping and receiving facility adjoining the Pentagon. It improves the physical security of the Pentagon by providing a separate location to receive items shipped to the building. The landscape roof provides space for native plants, allowing for water reuse where the parking lot used to be. The green roof aids in the reduction of storm-water volume leaving the site and heat loading of the facility.

The [renovation to the Pentagon that began in 1998](#) included the installation of blast-resistant windows, the removal of hazardous debris and asbestos (EPA 2009). Some of this section was destroyed during the 11 September 2001 attack, however, the blast-resistant windows lessened the potential of greater destruction. See Section 11 *Antiterrorism*, to read about the importance of antiterrorism measures in resiliency.

5 Tropical Cyclones

[Tropical cyclones](#) are rotating storm systems characterized by low-pressure centers, atmospheric circulation, strong winds, and thunderstorms that produce heavy rain (Wikipedia 2023a). Depending upon location, they are [known by other names](#) such as typhoons (West Pacific Region and Indian Ocean), hurricanes (Northeast Pacific and North Atlantic) and Cyclones (South Pacific; TornadoExtreme, n.d.). Cyclones have diameters that are several hundred miles. See Table 3 for how this is categorized.

Some of the biggest disasters in the world are [caused by cyclones](#); in 1839, a cyclone claimed 300,000 lives in India (TornadoExtreme, n.d.). An average of 10–15 cyclones occur within a year, and are measured with the Saffir-Simpson scale and the Beaufort scale which are determined by wind speed.

An article from Jennifer Chu at [MIT News](#) (2012) states that “researchers say by the year 2100, two factors could more than quadruple the economic damages caused by tropical storms in those regions and around the world: growing income and global warming.” They predicted that the worldwide annual damage from hurricanes because of population growth will increase from the current \$26 billion to \$56 billion in the next century, and with the factor of climate change, the annual damage could quadruple to \$109 billion. The areas impacted the most are North America, East Asia, Central America, and the Caribbean.

Buildings designed with resiliency in mind must strive to be hurricane-proof, especially in areas that are prone to this type of natural disaster.

5.1 Resources

Saffir-Simpson Scale:

<https://www.wtsp.com/article/weather/hurricane/saffir-simpson-hurricane-scale-how-to-measure-a-tropical-cyclones-strength/67-471059965>.

Beaufort Scale—Etymology and Classification:

<https://www.weather.gov/mfl/beaufort>.

Table 3. Beaufort Scale.

Beaufort scale	10-min Sustained Winds (knots)	N Indian Ocean IMD*	SW Indian Ocean MF*	Australia BOM*	SW Pacific FMS*	NW Pacific JMA*	NW Pacific JTWC*	NE Pacific & N Atlantic NHC* & CPHC*	
0–6	<28	Depression	Tropical Depression	Tropical Low	Tropical Depression	Tropical Depression	Tropical Depression	Tropical Depression	
7	28–29	Deep Depression					Tropical Storm	Tropical Storm	
	30–33								
8–9	34–47	Cyclonic Storm	Moderate Tropical Storm	Tropical Cyclone (1)	Tropical Cyclone	Tropical Storm	Typhoon	Hurricane (1)	
10	48–55	Severe Cyclonic Storm	Severe Tropical Storm	Tropical Cyclone (2)		Severe Tropical Storm			
11	56–63	Very Severe Cyclonic Storm	Tropical Cyclone	Severe Tropical Cyclone (3)		Typhoon			Hurricane (2)
12	64–72			Severe Tropical Cyclone (4)					
	73–85								
	86–89		Intense Tropical Cyclone	Severe Tropical Cyclone (5)	Hurricane (4)				
	90–99								
	100–106								
	107–114		Very Intense Tropical Cyclone	Super Typhoon			Hurricane (5)		
	115–119								
120	Super Cyclonic Storm								

* India Meteorological Department (IMD), Météo-France (MF), Australian Bureau of Meteorology (BOM), South West Pacific Fiji Meteorological Service (FMS), NW Pacific Japanese Meteorological Agency (JMA), Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC) & Central Pacific Hurricane Center (CPHC).

NOAA Mapping Billion-Dollar Weather and Climate Disasters—interactive map: <https://www.ncdc.noaa.gov/billions/mapping/freq/1980-2021>.

National Hurricane Center—track current tropical cyclones and forecasts: <https://www.nhc.noaa.gov/?atlc>.

5.2 Techniques

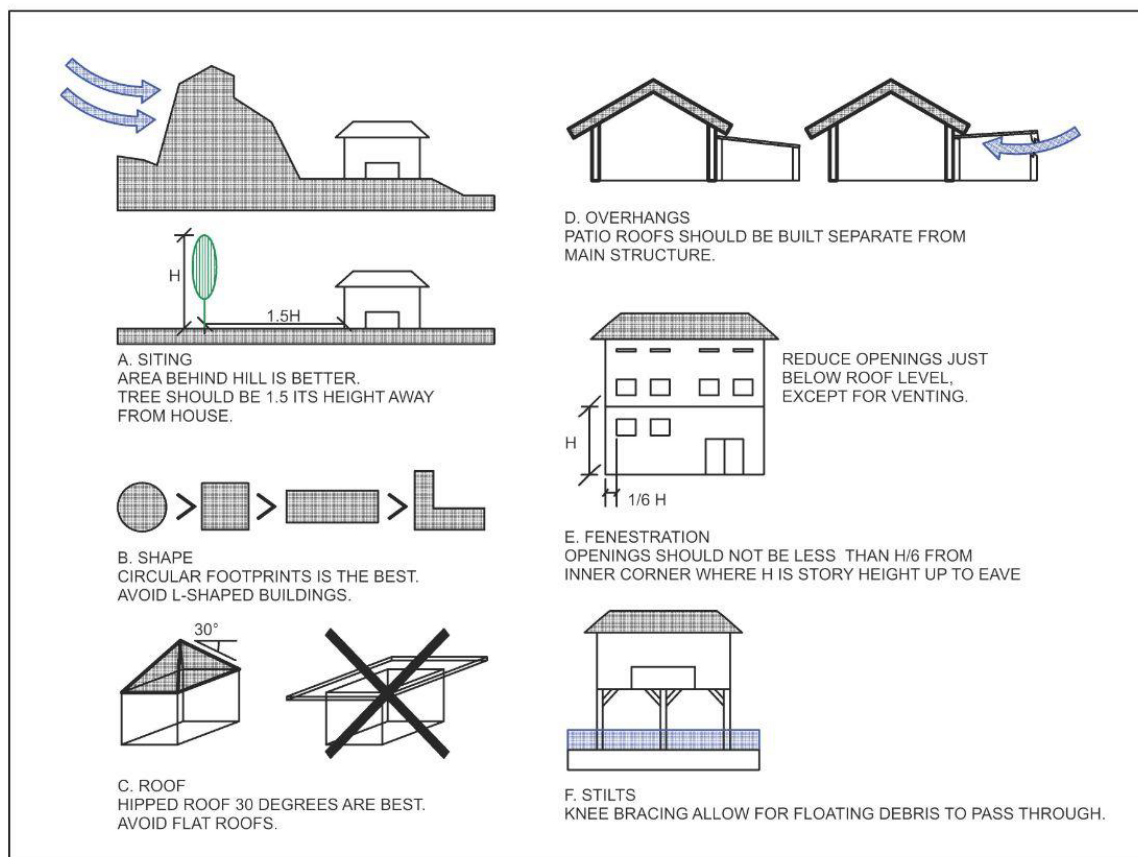
The [FEMA website](#) offers a collection of building science publications discussing how to plan, design, construct and maintain structures in hurricane regions (FEMA 2021b).

5.2.1 Siting

[The area behind a mound or hillock is preferred](#), as it provides a natural shielding from high winds (Agarwal 2007). Rows of trees planted uphill will also act as a shield; the area of influence is 8–10 times the height of the tree. The tree should also be planted at least 1.5 times its height.

In hilly regions, wind speeds are the highest along ridges and lower valleys. Some long narrow valleys may gain higher wind speed because of the tunneling effect. However, if construction is along the coast, place the site on higher ground to prevent inundation that could damage property severely. Water gathers along the valleys. See Figure 12, part A.

Figure 12. Techniques for designing for hurricanes.



DESIGNING FOR HURRICANES

5.2.2 Building Shape

Buildings designed in simple, compact, and symmetrical shapes are the best for withstanding cyclone impacts by not catching the winds that can cause damage to the structure. Circular footprints allow for the best wind flow, lowering wind resistance, as corners are usually the weakest spots.

The more compact and square the buildings are, the better they are at resisting higher wind speeds compared to rectangular buildings. L-shaped buildings should be avoided and the length of the building should not be more than three times the width (FEMA 2021b).

When erecting more than one structure the grouping of the buildings should not create wind tunnels, because gridded planning patterns create more wind tunneling. It is better to create zig-zag patterns to discourage wind. See Figure 12, part *B*.

5.2.3 Roof

Avoid lightweight flat roofs. The pitch of the roof should not be less than 22 degrees. Hipped roofs that are 30 degrees are tested to withstand wind the best. Hence, hipped roofs are preferred to gable roofs when designing in areas prone to hurricanes (FEMA 2021b).

Roofs should be braced by ties to the main structure to prevent uplift from wind. This can come in the form of hurricane clips. Additionally, tiles should be avoided as roofing material, as it could become debris during heavy winds and a danger to others. See Figure 12 part C.

5.2.4 Overhangs

Minimize overhangs on structures, as high wind force can build underneath them. When there are overhangs, they should not be more than 18 inches at the eaves.

Patio roofs should be built as separate structures rather than extensions from the main building. In cases of emergencies when the patio roof gets lifted from high winds, the main roof remains and does not also get destroyed. Lower edges of the roof should also [feature systems](#) that reduce local wind stresses (New Jersey Institute of Technology 2010). See Figure 12 part D.

5.2.5 Fenestration

Openings in load-bearing walls should be [no less than the distance of \$h/6\$ from inner corner](#), in which h is the story height up to the eave (CEC 2016). Avoid openings just below roof level, except for venting water in case of flooding. Openings should have strong holdfasts and closing and locking arrangements to create a tight seal.

Design thicker glass panes and reduce the panel sizes to smaller dimensions. This allows for lower probability for entire windows to fail. Strengthen the glass by pasting thin film or paper strips, which can reduce vibrations, and hold debris of glass in case of breakage. Additionally, avoid openings in roofs that cannot be securely closed during cyclones (sunroofs may not be the best idea). Hurricane resistant windows may be a good choice. The use of durable glass and materials will greatly reduce danger. See Figure 12 part E.

5.2.6 Hurricane shutters

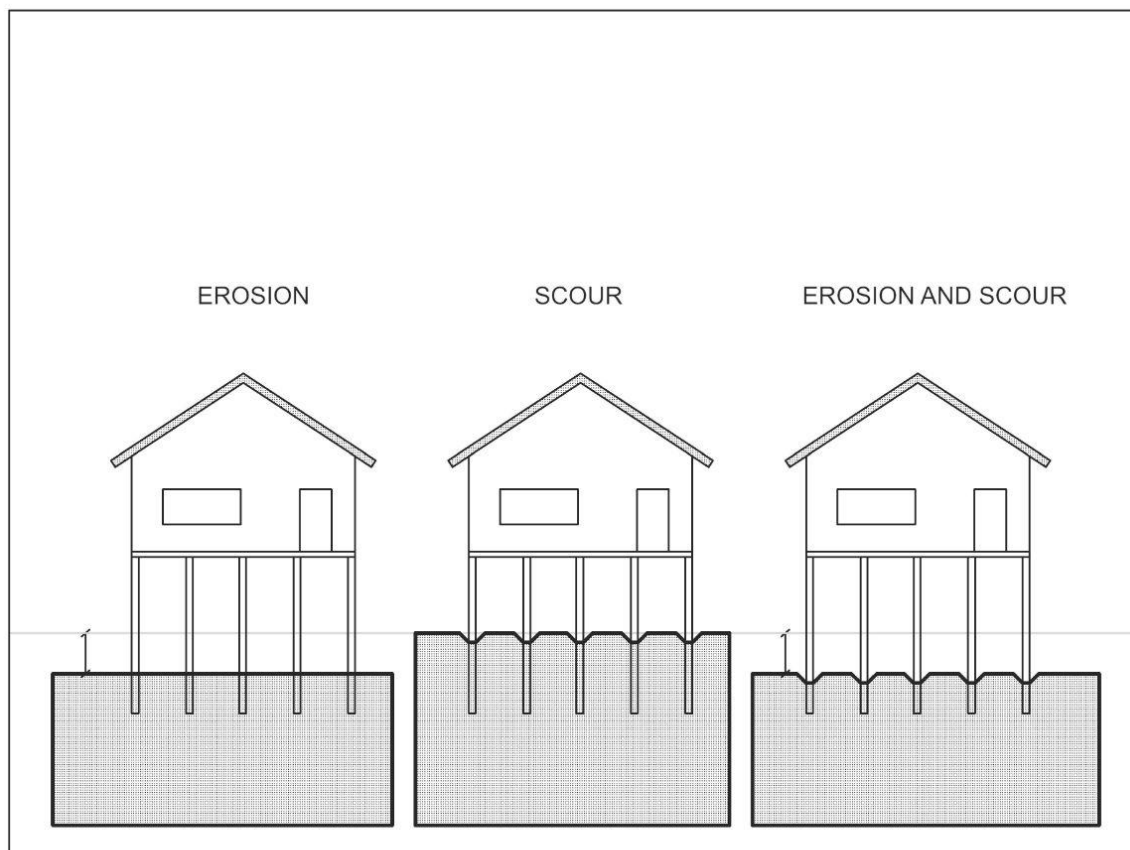
There are many kinds of [hurricane shutters](#) that have both pros and cons which are discussed in the following sections (Rothman and DiClerico 2022):

- Rolling—Remote controllable and allow for additional insulation and privacy
- Fabric—Economical, no professional installation needed, can be stored away, allow light in
- Temporary clear polycarbonate or steel—Requires additional hardware but are quick fixes
- Colonial shutters—Most stylish and visually appealing
- Bermuda shutters—Can act as secondary function of shade
- Sliding door or accordion shutters—Permanently attached to side of window

5.2.7 Foundation

Foundations should be designed to withstand high wind loads and consider the impacts of flooding (FEMA 2021b). Flooding can affect the safe bearing capacity of soil. Scour from a receding tidal surge needs to be considered when constructing the foundation. See Figure 13 to see the difference between erosion and scour.

Figure 13. The difference between scour and erosion.



SCOUR AND EROSION

5.2.8 Lifted living space and stilts

Building on stilts can help prevent inundation. Make sure the stilts are braced in both principal directions. Knee bracing is better than full diagonal because it allows for floating debris to pass during a storm surge.

Open foundations with deeply driven piles should be used in beach front sites. Closed foundations are less expensive but should be used only inland where there is less risk of inundation. See Figure 12 part *F*.

5.2.9 Structural reinforcements

The structural system of the building should be designed to withstand the force and pressure of high winds and inundation caused by storms. The connections between the different building elements are key to ensuring that the building protects its inhabitants.

5.2.10 Power

Plans for alternative sources of backup electricity should be in place for times of emergency, such as solar, because sunlight is especially plentiful after a storm. Backup generators and diesel fuel tanks are also useful. Solar generators may be useful in times of crisis. Solar water heaters could provide hot water in the event that utilities are not available.

The Electricity Demand Response Program is for when the local power grid is in danger of an outage (for example during heavy use during a heat wave), a facility can go off the grid to help stabilize the system. A facility can receive money back when called upon to disconnect from the grid. This compensation can help recoup initial investments in resilience-enhancing services.

It is recommended to protect HVAC equipment by elevating it minimum 20 feet, and waterproofing it. Remove outdoor equipment so that it does not become debris that damages other equipment or structures. Remove air conditioning wall units and seal the opening before a storm and turn off circuit breakers during storm which will prevent water from entering the structure and prevent electrical injuries.

A storm might knock out power impacting the refrigerator; so place emergency food storage in an elevated area. Fortification of central energy plants and cooling towers to provide cooling after hurricanes is also important. Freezing water bottles in the freezer before a storm could also extend the effectiveness of the freezer for food preservation. The melting water bottles can then be used for drinking water.

5.2.11 Waste

Turn off the main water line to prevent water from becoming contaminated during a storm event. Open the tap furthest away from main line so air can still get into the plumbing system. Turn off the water heater to avoid pressure on the plumbing system.

Sump pumps redirect over-land water and groundwater away from the house. Backflow valves are also important to prevent water from entering the home through the sewer and water systems.

Potable water tanks should be installed for backup water, and septic tanks are also important after a storm event.

5.2.12 Community approach (Koban)—emergency shelters

Public spaces should be designed so that they can become areas of temporary emergency shelters for displaced people; it is important that they are designed with the intention of multiuse and to hold a large population. For example, hospitals can be a place of shelter for the community. Backup power supply could be shared with the community. Additionally, it is important that these emergency shelters also provide an abundance mental-ity to create a sense of security, reduce panic (reduce sense of scarcity) until further aid is available.

An example of an emergency area is the Koban in Japan. [Koban](#) are small one- to two-story buildings staffed with uniformed police implementing community management (Wikipedia 2022b). They serve as a general watch, respond to emergencies, give directions, serve as a lost and found place, and interact with citizens in a more intimate setting. The services offered at the Koban allow for a feeling of safety in the community and a quick resource for people during times of emergencies. The Los Angeles Police Department has a Koban in the United States [at The Grove Mall in Los Angeles, California](#) (Sellars 2016). There is another one located in Little Tokyo, Los Angeles, California.

5.3 Precedents

5.3.1 Prefabricated hurricane homes

[Prefabricated homes](#) for hurricane-prone areas have similar characteristics that make them optimal for surviving heavy flooding and wind (Topsider Homes 2023). They are usually designed with a [circular footprint](#), minimizing wind uplift (Bendix 2019). Overhangs and outdoor decks are minimized, and those features are even further minimized if the building footprint is not circular. See Section 5.3.3, *Sand Palace—Mexico Beach, Florida* precedent for an example of a hurricane-proof home that is rectangular.

The main living spaces are usually raised on stilts or constructed over a thick reinforced concrete base—utilizing the sacrificial basement technique. The open foundations are often used for storage and parking. Whether the structure is raised on stilts or with reinforced concrete, the

design allowed for water and debris to flow through and escape. The raised elevation of these coastal homes also allows for panoramic views.

5.3.2 Cubicco prefabricated hurricane dwellings

[Cubicco](#), a Dutch company developed a [flat-packed, module, prefabricated, hurricane proof home](#) that costs less than \$200,000 to build (Ngyuen 2016). The buildings are made with laminated wood and cork, designed to withstand high winds of 185 miles per hour. The modular dwelling units could be elevated on stilts, disassembled for moving, and easily assembled by trained workers in the desired location. The modularity also allows for different kinds of combinations for different uses, such as a home or an office. Additionally, the unit has the option to be paired with solar panels on the roof, open slats for geothermal heating or cooling, and a water reclaiming system.

5.3.3 Sand Palace—Mexico Beach, Florida

After Hurricane Michael, a category 4 storm, hit Florida in 2018 with sustained winds of 155 miles per hour, three quarters of the homes on Mexico Beach, Florida were completely destroyed. However, [Sand Palace](#), which is only 150 yards from the coast, survived miraculously because of preparation and hurricane-resistant design (Cummins 2018).

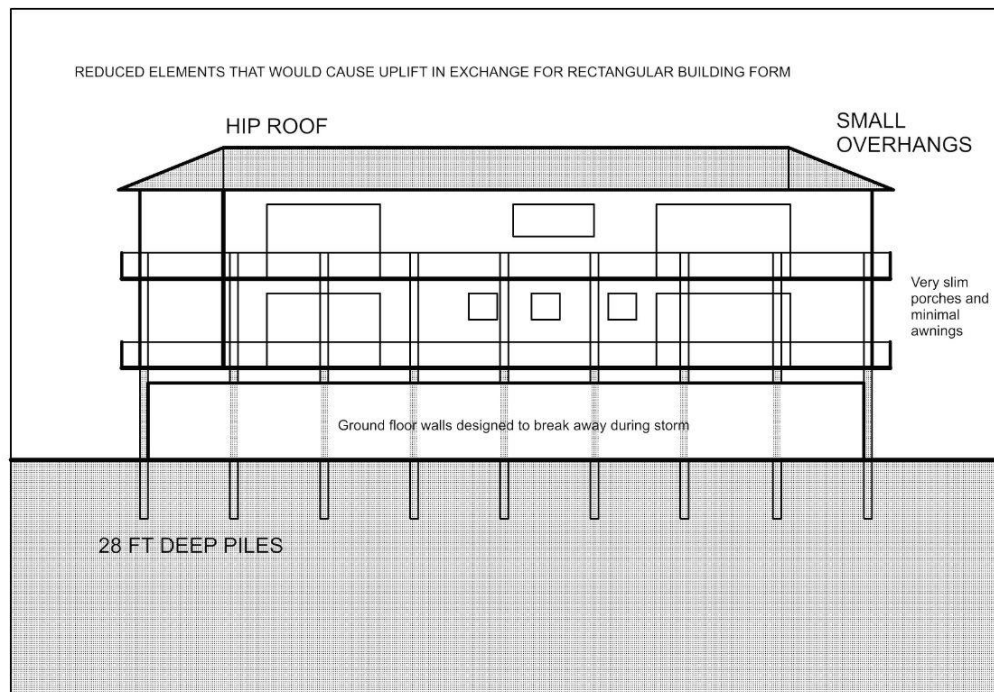
In exchange for a wider and rectangular facade facing the coast, the awnings, decks, and overhangs are extremely slimmed down. Usually, homes designed to withstand hurricanes are circular or square to minimize wind uplift. The ground floor was designed so that the walls would break away; the wooden slabs looked like normal walls during normal conditions, but were nonload-bearing. The home is lifted on stilts, and the ground floor is used for storage. Though the house was flooding, it did not impact the occupants inside as much as it would have if inundation was not anticipated. Additionally, the walls were constructed of insulated concrete forms in the upper floors, resisting the increased pressure of the storm surge during the hurricane.

Additionally, the piers are concrete pilings that dive 28 feet into the sand, and the living spaces of the two occupied upper floors start 24.4 feet higher than the sea level. Windows were designed with laminated interior panes, allowing debris to stay in place when the windows broke because of the increased pressures during the hurricane. The spider-web effect of this

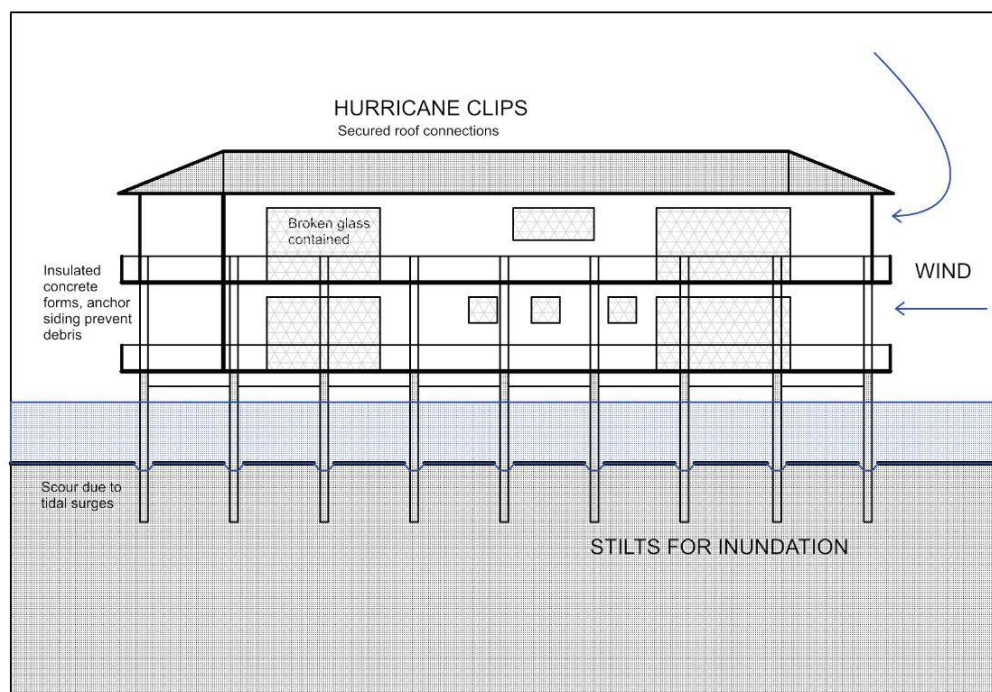
glass helps prevent additional wind from entering the home and causing possible implosion.

The roof is constructed of 26-gauge steel, tightly sealing the interior in the hip-roof style with four sloping sides which is the best for withstanding hurricane-force winds. The connections between the structure and main-frame was strengthened with hurricane clips and Simpson strong ties (see Figure 14).

Figure 14. How the Sand Palace was built for inundation during hurricanes.



SAND PALACE



SAND PALACE

5.3.4 Seagate Rehabilitation and Nursing Center—Brooklyn, New York

[The medical facility](#) is elevated 30 feet above ground with parking underneath (USCRT 2017). It is equipped with an emergency backup power supply to completely power medical equipment, HVAC, and elevators without connection to the city's power grid. The first floor contains only the lobby and support services. Community and administrative space are located on the second floor, and patient rooms are on the third floor. This means that the space layout was intentional, placing critical programs on the highest floor and the minor spaces on the ground floor, prioritizing the safety of occupants and operation of the hospital in the case of flood.

When Hurricane Sandy caused storm surges along New York and New Jersey coasts, the emergency power generators remained safe and supplied enough backup power for four days despite the widespread power outage in the area. The preparation of food and medical supplies also allowed staff and patients to shelter in place while there was a delay in emergency supplies and limited transportation. Seagate Rehabilitation and Nursing Center allowed continual operation through the disaster and also assisted the local community.

5.3.5 Greenwich Hospital—Greenwich, Connecticut

Hurricane Sandy caused more than \$65 million in damage on 29 October 2012. At its peak, the storm cut electrical power to more than 8.5 million customers. [Greenwich Hospital's](#) power infrastructure is a key example of power resilience during Hurricane Sandy (USCRT 2018). Even as power went out in the surrounding area for an average of 7 days, the hospital was able to continue its functions, admitting 20 new patients during the emergency, and housing 150 additional staff members.

The 175-bed hospital installed a combined heat and power (CHP) system that consisted of two 1,250 kW natural gas-fired reciprocating engines. According to The USCTR (2018), "they also installed a 2,000 kW backup generator and received ENERGY STAR certification in 2010 and 2011. This CHP system runs 24 hours a day, 7 days a week, except during routine maintenance. The hospital uses the systems' thermal output for hot water and space heating. The CHP system saves energy, reduces greenhouse gas emissions, and significantly improves the hospital's resilience."

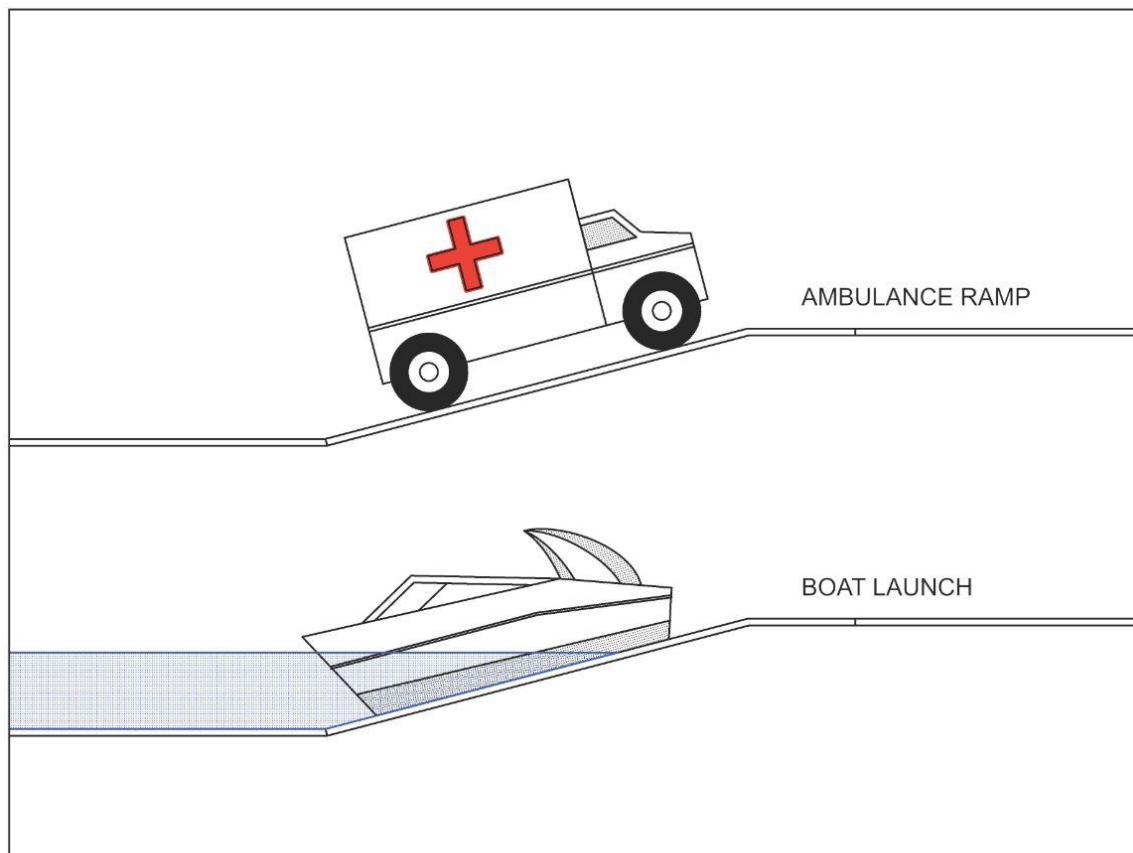
The hospital participates in an electricity demand response program, allowing them to receive \$30 per kW when called upon to disconnect from the city's power grid. This helps with the cost to maintain the extra infrastructure for power resiliency.

5.3.6 Project Legacy for Veterans Affairs (VA)—New Orleans, Louisiana

This [medical facility](#) was designed for resilience after the 2005 Hurricane Katrina destroyed the previous Veterans Affairs (VA) hospital (NBBJ, n.d.). Mechanical and electrical infrastructure is housed in the upper levels to prevent damage from severe flooding. Building enclosure and windows are designed to survive at least a Category 3 hurricane. Emergency departments and patient beds are located at least 20 feet above the established FEMA Base Flood Elevation. The kitchen is placed on the fourth floor, while the cafeteria is on the ground floor. This is prioritization of program functions that are mission essential. Visitors can also travel from building to building completely indoors without being affected by outside flood waters.

Recovery efforts for evacuation and emergency help for disaster relief posthurricane was also implemented. Flexible use of a dedicated ramp for ambulance access to the VA hospital can double as a boat launch. The parking structure on the roof can serve as a heliport for emergency evacuation. See Figure 15.

Figure 15. Flexible double use of the same type of architectural form, as an ambulance ramp during normal operations and as a boat launch during climatic emergencies.



FLEXIBLE DOUBLE USE

The building stores 320,000 gallons of fuel to operate for a full week. The 6,000 square foot warehouse stores emergency supplies to support 1,000 people. The building also collects and stores over a million gallons of rain-water on site, reducing the demand from water utilities for cooling systems and reducing load during normal operation. It also acts as a backup water supply during times of emergency. The on-site sewage treatment system is capable of processing and holding waste for 5–7 days. Hurricane resilience combines multiple aspects of adaptability: water, power, and flooding.

6 Tornadoes

[Tornadoes](#) are narrow, violently rotating columns of air that extend from a thunderstorm to the ground (NSSL, n.d.). According to NOAA, about 1,200 tornadoes hit the US yearly. Like hurricanes, these storms are characterized by strong winds, [but unlike hurricanes](#), they can come with heavy rainfall, hail, and sleet (TornadoExtreme, n.d.).

Tornado Alley refers to the area of high tornado occurrence in the United States, however tornadoes can occur anywhere in the fifty states. The peak season for tornadoes in the Southern Plains (Texas, Oklahoma, and Kansas) is early May to early June. On the Gulf coast, it is early spring, and in the Northern Plains and Upper Midwest (North and South Dakota, Nebraska, Iowa, and Minnesota) it is in June or July. For more statistics [see the NOAA site](#) for areas in the US most affected and when (NOAA-NCEI 2023).

Tornadoes are measured with the Fujita (F), Enhanced Fujita (EF), and TORRO (T) scale. A zero on these scales—Fo, EFo, or To—means minimal damage (trees not buildings), F5, EF5, T11 for high damage (buildings and skyscrapers damaged). [In the United States, 80% of tornadoes fall into the EF0 and EF1 category and less than 1% are violent](#) (EF4, T8 or more) (Diffen, n.d.). See Table 4 for a breakdown of the relation of wind speed to amount of damage.

Table 4. Enhanced Fujita Scale. Table derived from [Fujita Tornado Damage Scale and “Storm Prediction Center WCM Data.”](#)

Fujita Scale				Enhanced Fujita Scale	
Scale	Frequency	Fastest ¼ Mile (m/h)	3 Second Gust	3 Second Gust	Potential Damage
0	44.14%	40–72	45–78	65–85	Light
1	33.24%	73–112	79–117	86–109	Moderate
2	16.17%	113–157	118–161	110–137	Significant
3	4.35%	158–207	162–209	138–167	Severe
4	1.01%	208–260	210–261	168–199	Devastating
5	0.10%	261–318	262–317	200–234	Incredible

However, tornadoes are incredibly hard to predict and once there is a tornado warning, people have very little time before the storm hits. It is important to design buildings that are resilient toward this phenomenon.

6.1 Resources

NOAA Mapping Billion-Dollar Weather and Climate Disasters—interactive map:

<https://www.ncdc.noaa.gov/billions/mapping/freq/1980-2021>.

NOAA Weather Service Forecast Office—tornado warnings indicate that people need to act now to find shelter:

<https://www.weather.gov/>.

NOAA Storm Prediction Center—tornado watch scans US for favorable conditions for storms;

<https://www.spc.noaa.gov/>.

Tornado Tracking:

<https://www.ustornadoes.com/tornado-tracking/>.

Cell phone alerts for severe weather:

<https://weather.com/news/news/2021-03-25-how-to-get-wireless-emergency-alerts-cell-phone-severe-weather>.

CDC—staying safe in a tornado:

<https://www.cdc.gov/nceh/features/tornadosafety/index.html>.

6.2 Techniques

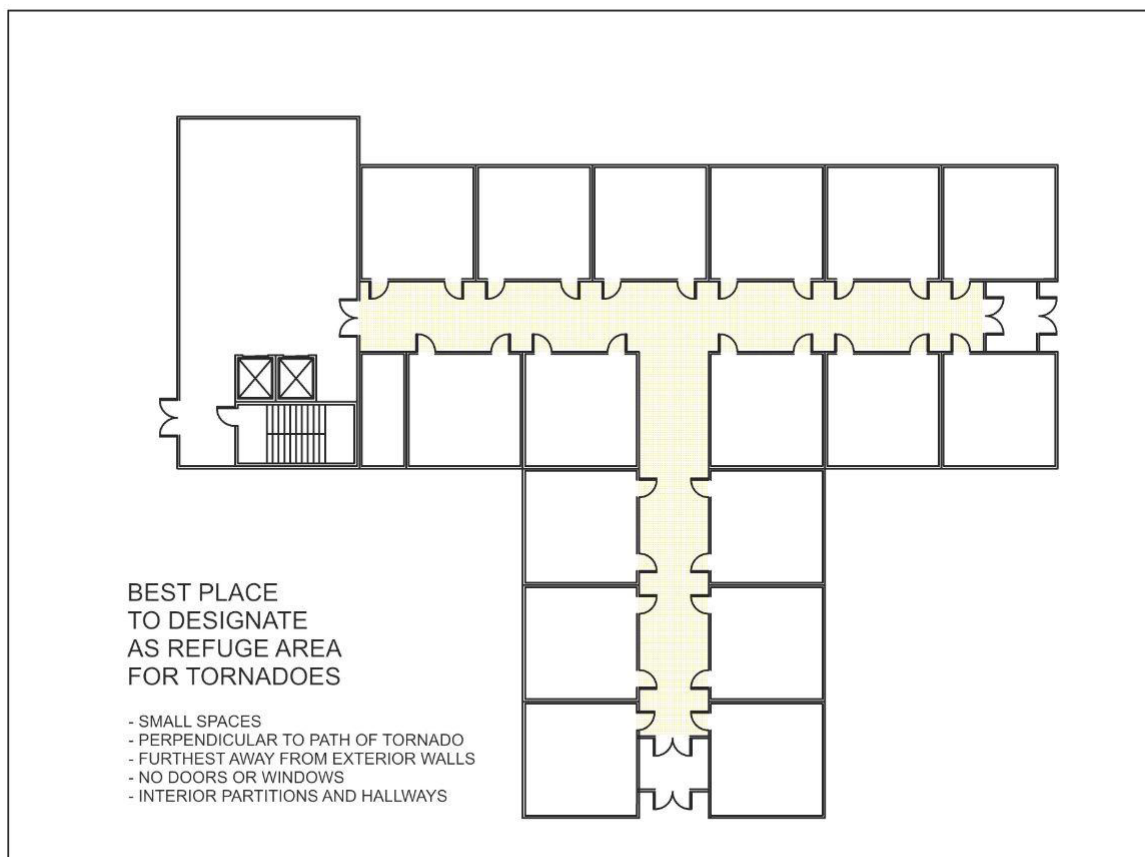
6.2.1 Safe rooms and storm cellars

Safe rooms are hardened structures specifically designed to meet the [FEMA criteria](#) and provide near-absolute protection in extreme wind events (FEMA 2021d). Occupants inside the safe room will have a high probability of being protected from injury or death. Refer to the following standards for constructing tornado safe rooms:

- [*ICC \(International Code Council\) 500 Standard for the Design and Construction of Storm Shelters*](#) (ICC 2020)
- [*FEMA P-361 Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms*](#) (FEMA 2021e)
- [*FEMA P-320 Taking Shelter from the Storm: Building or Installing Safe Room for Your Home*](#) (FEMA 2021f)

Designated areas of refuge in a building are usually small spaces that are perpendicular to the path of the tornado. They are furthest away from the exterior walls and devoid of many windows or doors, protecting occupants from flying debris. Interior partitions and hallways offer the greatest protection when they are fitted tightly to the roof or floor. Refer to [*FEMA P-431 Tornado Protection: Selecting Refuge Areas in Buildings*](#) for more information (FEMA 2009). See Figure 16 for areas in a building that are the best for refuge.

Figure 16. Refuge areas inside a building.



REFUGE AREAS INSIDE A BUILDING

[Storm cellars](#) are built close to the home to allow for instant access during an emergency (Wikipedia 2022e). The doors are mounted at an angle instead of perpendicular to the ground to prevent occupants from getting trapped underneath. Usually they are built around eight by twelve feet for single family homes, entirely underground. Sometimes, storm cellars are equipped with geolocation services to assist in ensuring recovery after the storm is over.

It is also beneficial to have community shelters built in schools or community centers that could be overengineered to withstand heavy wind conditions and adverse weather. Shelter spaces should contain the following safety equipment:

- Flashlight; one per 10 occupants
- Fire extinguisher; safe for use with human occupancy
- NOAA weather radio; with charging batteries
- Radio; with batteries for receiving public broadcast
- Extra batteries
- Audible sounding device that operates without power (e.g., canned air horn) to signal for rescue in case entrance is blocked

6.2.2 Heavy building materials

Materials such as masonry or concrete that are well tied to all other building components have a higher chance of surviving high winds associated with tornados. The weight of these materials will help resist uplift and lateral loads. Lightweight roofing and siding materials like gravel and insulation, shingles, and brick veneer, and roofing membranes could become debris (FEMA 2009).

6.2.3 Roof

Do not build flat roofs or large overhangs that can become places where the wind uplift pressure increases. Instead, use hipped roofs, which have been shown to demonstrate the highest resilience toward high winds. Short span roofs are more likely to remain intact; avoid making areas that utilize long span roofs (gyms, auditoriums, multipurpose rooms) and lightweight roofs as areas of refuge.

The ICC also advises the use of [enhanced nailing patterns](#), with more nails and closer spacings can also keep roof decks attached to roof trusses (Cube 2021).

6.2.4 Fenestration

The combination of internal pressure and outward pull can cause buildings to fail. Doors and windows should remain closed on all sides of the building to block out as much wind from entering. Avoid large glass windows.

As discussed in Section 5 *Tropical Cyclones* resilience, doors and windows could benefit from shutters to prevent wind-borne debris and other projectiles from breaking the glass. However, time may not permit the usage of manual shutters that require time for preparation.

6.2.5 Building below ground level

Upper floors are more vulnerable to wind damage. Locate safe spaces for occupants during a storm.

6.2.6 Power

Backup generators could serve as emergency power during shelter. Solar generators are a great source of power after the storm because sunlight is usually plentiful after the disaster.

6.3 Precedents

6.3.1 Rebuilding Joplin, Missouri after the 2011 tornado

The St. Bernard Project, a New Orleans, Louisiana based nonprofit that specializes in construction after natural disasters, partnered with Rebuild Joplin to deal with the aftermath of the tornado. There is a tremendous amount of rebuilding that happens after a severe storm event that is usually not accounted for when planning for resilience. [Consequences could lead to a rise of abuse, domestic violence, suicides, and mass homelessness](#) because of economic tolls (Shenolikar 2016).

Recovery and construction costs totaled more than \$1.6 billion, and over three years. The amount was eased with the organization of volunteers and planning to increase efficiency in transporting materials and tools for the rebuilding of Joplin, Missouri.

6.3.2 Mercy Hospital—Joplin, Missouri

The [hospital](#) reopened in March 2015 and was rebuilt to withstand high winds. It has two underground levels (USCRT 2019). Critical care areas are designed with windows that could resist 250 miles per hour winds. It comes with two generators housed within the building that can function independently to provide enough power for the entire hospital. It is also equipped with reinforced core, where the stairwells and elevators are; this helps minimize the wind damage from preventing egress. See Section 2.4.2 *University of Oklahoma Medical Center—Oklahoma City, Oklahoma* precedent.

6.3.3 FEMA Protecting School Children from Tornadoes—mitigation case studies

The [Wichita Public School District](#) in Wichita, Kansas helped spur the construction of shelter programs in other schools across the state (FEMA 2002). Under the guidance of FEMA P-361 (2021d), these school districts enabled the design and construction of [economical shelters](#) that make use of school space to meet the needs for structural strength, accessibility, reliability, and comfortability (FEMA 2021c).

In the document, the case study of Kapaun Mount Carmel Catholic High School depicted the use of safe rooms, relocating all students, faculty, and staff to the underground safe room in the new Science and Technology Wing of the building.

Another case study is of Jefferson Elementary School. A multipurpose room is constructed with precast concrete wall panels and precast concrete double-T beams. The hallways are designated refuge areas. There was an alcove entrance designed to minimize the potential for wind and debris damage to the exterior door.

6.3.4 Unified School District Number 422, Greensburg K-12 School—Greensburg, Kansas

A massive tornado destroyed 95% of Greensburg, Kansas in 2007. The original school building was also destroyed, so the new school was [completely redesigned and reconstructed](#) (DOE 2011). The two story building was built with numerous renewable energy technologies including a 50 kW on-site wind generator and ground source heat pump system, which will pay for itself in 11 years. The design of the new school building implements

the [use of natural light](#) that floods into classrooms, gymnasiums, offices, which reduced electric demand for lighting (Eckels 2010). The lockers are constructed with recycled plastic. Being LEED Platinum, the new structure is incredibly sustainable, but also depicts great resilience to reopen and re-operate after a destructive event.

6.3.5 Xenia Senior High School—Xenia, Ohio

[The school, a two story, slab-on-grade building](#) without a basement, was struck by a tornado in April 1974 (FEMA 2009). Luckily, it was after school dismissal. All windows on the west and east sides were blown into the interior. The load-bearing masonry wall of the long-span rooms failed, causing the roof to fall in. Debris entered the school and became dangerous missiles.

After a study was conducted on the damage, the only portion of the building that offered refuge was the lowest first floor. The smaller spaces remained intact and corridors that were perpendicular to the storm path offered protection. The concrete structural frame also remained intact. The heavy concrete roof was also safe where supports were rigid frames. The concrete block interior partitions prevented missiles and debris from entering in some areas.

7 Fire

The *Fire Triangle* includes three facets to all fires; heat (something to ignite or combust), fuel (a material to burn), and oxygen (to allow the fire to exist, grow, and rise) (NFPA, n.d). According to NOAA, July 2021 was the hottest recorded month in human history. Temperatures are projected to increase annually. Global warming creates drier and hotter climates, which encourages wildfires. Wildfires emit greenhouse gases that contribute to global warming; thus the cycle continues. Fires destroy acres of forests and property around the world. In the United States from January to August 2021, there were 40,474 wildfires, compared to 35,878 in the same period in 2020. Approximately 4.3 million acres of California were burned in wildfires 2021 (CAL FIRE 2021). Fires worsen air quality by injecting soot and other aerosols into the atmosphere. Fires can be deadly for people, wildlife, and ecosystems. Ninety percent of wildfires are caused by human activity.

7.1 Resources

Fire and Smoke Map:

<https://fire.airnow.gov/>.

Air AQI (air quality index) per zip code:

<https://www.airnow.gov/>.

National fire statistics:

<https://www.nifc.gov/fire-information/statistics>.

Elide Fire Extinguishing Ball:

<https://www.elidefire.fr/home>.

F.A.C.E. Fire Wildfire Prevention Extinguisher:

<https://www.facefires.com/meetface>.

7.2 Techniques

7.2.1 Natural succession

To facilitate a resilient recovery from wildfires, one must consider the environmental and financial factors involved. After a wildfire has been contained or extinguished, it is advised to avoid or minimize restoration cost for personal property or land destroyed and damaged. This would

include the home, possessions, and landscaping. Restoration and renovation costs only make these frequent disasters more expensive. Constant spending on the maintenance of wildfire prone landscapes and recently destroyed areas is not resilient or economically sustainable. Instead, it is prudent to allow for ecological succession. By letting ecosystems recover naturally, restoration funds can be used in more practical locations or for more resilient measures.

7.2.2 [Community preparedness](#)

It is also important to consider the steps to creating a community resistant to wildfires. Currently there are relief funds and initiatives for victims of wildfires and displacement. Supporting and amplifying programs like these are the first step to full recovery and resilience.

Implementing automatic fire extinguishers in structures (eliminating fire without manual activation) will ensure that disasters will be taken care of even when occupants are not around or not awake to tend to them. Assisting residents in wildfire prone areas to obtain and install these devices can save lives, property, and resources.

Planning and designing effective egress methods for communities and ingress methods for emergency vehicles are also very important. This will improve response times, safety, and organization.

Other infrastructure to consider is solar panels or underground electricity in lieu of power lines. Often when wildfires disrupt communities, they knock down power lines in the process. This ruins electronic and connectivity capabilities during an already detrimental time. Underground electrical infrastructure and solar panels will help keep resources available to at risk occupants in their time of need (Buettner et al. 2008).

7.2.3 Landscape treatments

7.2.3.1 *Thinning*

Limiting and controlling the fuel of wildfires (trees and vegetation) can ultimately decrease the level of destruction done to the ground and the air. Eliminating flammable, invasive plant species, and implementing landscape thinning in at risk areas will reduce the amount of fuel available for

a wildfire to spread. Pruning tree branches and removing clusters of trees will slow down the spread of fire.

7.2.3.2 Fire breaks

Adding fire breaks—gaps between areas of landscaping—creates a buffer zone and contain fires when they occur.

7.2.3.3 Prescribed burns

Prescribed burns are another method that is frequently used to treat at-risk areas before wildfires begin. This indigenous practice involves treating a desired area with a controlled fire. Scientific calculations and data determine the fire's objectives, size, fuels, and environmental conditions as well as how these fires will be suppressed. Prescribed burns can also control invasive species and encourage biodiversity.

7.2.4 Architectural considerations

When designing a building, several exterior features should be considered. Building placement should be away from tall trees and excess shrubbery. Minimal landscaping is preferred. The building envelope should consist of little to no south facing glass or windows facing woodlands. Glass facades will allow heat to enter the building much quicker. Avoid long overhangs, open decks, or other spaces where fire can spread under.

7.2.5 [Building materials](#)

Structures should include patios, driveways, fire retardant low growing plants, or crushed stone around the perimeter. Roofs should be built from Ignition Resistant roofing material, Class A fire rated standing seam, tile, slate, or composite roof. Doors should be Ember Resistant exterior metal panel, and windows should be Double pane tempered glass, with nonflammable shutters. Exterior building materials should avoid acrylic skylights. Non-flammable fiber-cement siding, Cultured Stone, brick, or stucco is preferred for the exterior (USFS, n.d.).

7.3 Precedents

The following resources and examples can be used to set a precedence for fire mitigation and developing resiliency:

National Park Service plans third prescribed fire at Monocacy National Battlefield:

<https://www.nps.gov/mono/learn/news/2021-prescribed-fire-at-monocacy.htm>

Department of the Interior, Region 1, National Capital Area Utilizes Prescribed Fire as a Management Tool:

<https://www.nps.gov/articles/000/prescribed-fire-in-national-capital-area.htm>

An engineer spent 15 years fireproofing his California home. Here's why his house was the last one standing after a devastating blaze of 2021:

<https://www.businessinsider.com/california-fire-fireproof-home-sonoma-county-kincade-2020-2#these-are-the-massive-batteries-that-provide-power-for-arais-off-grid-home-he-hand-poured-the-concrete-his-basement-floor-is-made-of-11>

The fire-resistant home is coming to California, and here's what it looks like:

<https://www.sfgate.com/california-wildfires/article/The-fireproof-home-is-coming-to-California-and-14102417.php#taboola-1>

8 Air Quality

Wildfires can cause temporary large increases in outdoor airborne particles, and substantial increases in gaseous air pollutants. Approximately 80% of total [exposure to particles from wildfires](#) will occur indoors (IAQ, n.d.). Buildings with low efficiency or no particle filtration systems will experience an increase in indoor air concentration of particles from wildfires (usually within residential buildings). Some health concerns from exposure to air pollutants include coughing, wheezing, harmful effects on eye and nose, respiratory infections such as colds, bronchitis, and pneumonia, inflammation, and death. The elderly, youth, and those with preexisting conditions are at the highest risk of air quality related health issues. Though helpful for limiting wildfire destruction, prescribed burns also contribute to premature deaths yearly. As wildfires continue to burn around the world, purifying and filtering indoor air must be made a priority to sustain a healthy community.

In urban areas where wildfires are less prevalent, air quality is still a major issue. In cities, the air quality is affected mostly by traffic emissions. Because of the number of vehicles and the high population in a specific area, there becomes a large concentration of particles in one area and a high exposure rate for dense communities. Understanding urban air quality resilience and different responses to combat harmful emissions will positively affect a substantial percentage of the global population. According to the United Nations, [55% of the world's population](#) live in urban areas (UN 2018).

Another global issue currently affecting us is the ongoing pandemic with COVID-19 and its mutating variants. To create a resilient community against diseases that can be transmitted through the air, one must consider strategies that produce healthy indoor environments. Proper sanitization, ventilation, and filtration are necessary to ensure safety. Other building systems and operations will help with resiliency.

8.1 Resources

Air AQI per zip code;

<https://www.airnow.gov/>.

Enhancing health with indoor air;

<https://sftool.gov/learn/about/626/enhancing-health-indoor-air>.

Sustainable response to COVID-19;

<https://sftool.gov/learn/about/625/sustainable-response-covid-19>.

Six questions to ask about COVID and air quality at work;

<https://www.nytimes.com/2021/09/13/well/covid-indoor-air-quality.html>.

What is carbon neutrality and how can it be achieved by 2050?

<https://www.europarl.europa.eu/news/en/headlines/society/20190926ST062270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050>.

8.2 Techniques

8.2.1 Air filtration systems

Including high efficiency particulate air filters and purification systems are one of the most effective ways to defend indoor air quality from harmful particles in the air. HEPA filters can remove dust, pollen, radon, asbestos particles, and more particulates as small as 0.3 microns. Activated carbon filters rid the air of contaminants, allergens, and odors because of its porous and absorbent properties. They are also used to absorb impurities in water. Paired with HEPA filters, they can eliminate 99% of all impurities in the air.

Other types of filters include ozone generators, electrostatic precipitators, and UV light air purifiers. These methods vary in efficiency and emit different volumes of harmful ozone into the air. Use these filtration methods for buildings with low occupancy to reduce exposure (Lesavoy 2016).

8.2.2 Plants and green walls

Adding greenery to indoor spaces is proven to remediate indoor air quality. Plants naturally absorb and catch pollutants in the air or trap them in the soil they are planted in. Green walls, both interior and exterior, have positive effects on the air quality. According to research from [Universities](#)

[of Birmingham and Lancaster](#), up to a 30% reduction in air pollution can be achieved by greening up city streets (University of Birmingham 2012). Interior green walls have even higher levels of efficiency. Studies have shown that particulate matter can be reduced by 50% in interior settings and nitrogen dioxide decreased by 60%. Green walls work to cool hotter temperature air through the process known as evapotranspiration; the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants. In cooler weather, the green walls can act as a layer of insulation. This will reduce heating and cooling costs in buildings and will allow for energy savings. Implementing green walls and plants in or on a building can help the project earn WELL® credits and LEED points. Green walls are also linked to biophilic benefits such as positive mood, productivity, reduced stress, and memory improvements.

See Table 5 for specific plants that work best at removing common pollutants in buildings (El-Tanbouly et al. 2021).

Table 5. Removal of common pollutants with plants

Common Pollutants	Plant Type
Formaldehyde (CH ₂ O)	Peace lily Boston fern English ivy
Carbon monoxide (CO)	Spider plant Janet Craig Dracaena Ficus
Volatile organic compounds (VOCs)	Golden Pothos Devil's ivy Philodendron
Trichloroethylene (TCE)	Mother-in-law's tongue Chrysanthemum Dracaena
Benzene (C ₆ H ₆), Toluene (C ₇ H ₈), Xylene (C ₈ H ₁₀)	Kimberly Queen Fern Orchid Dieffenbachia

8.2.3 Ventilation

Fresh air intake into buildings help maintain a healthy indoor environment and facilitate air movement. It can help remove pollutants, moisture,

odors, and smoke. Buildings with large amounts of moisture in the air are prone to mold and mildew. These buildings are also more likely to carry viruses and germs in the air, putting occupants at risk of sickness and diseases. Humid air allows viruses and bacteria to stay in the air longer. Ventilation is a great technique to combat humidity and illnesses by circulating air into the building while driving out pollutants. It is recommended to have operable windows and to use ceiling fans for efficiency. Ventilation can also reduce the risk of asthma, allergies, and headaches.

8.2.4 Decreasing use of internal combustion engine vehicles

Since a significant amount of pollution comes from traffic emissions, there is the need to decrease and or eliminate the use of gas vehicles in our urban areas. Promoting electric vehicles, buses, and other infrastructure will have a dramatic effect on our air quality. Tesla's 2020 report shows that their electric cars have avoided 5 million tons of carbon dioxide emissions in just one year (Tesla 2020). No longer being dependent on gasoline will make for a more resilient community as resources become limited and scarce. Improving walkability and cycling in communities means more sidewalks, trails, pedestrian bridges, local grocery stores and bus stops, parks, bike lanes, and bike racks or lockers. The *15 Minute City theory* is a great example of encouraging walking, cycling, and short modes of transportation to everyday destinations. Adding urban design principles that encourage walking and biking can help cut traffic emissions in half (Schauenberg 2023).

8.2.5 Carbon removal strategies

Carbon removal technologies are quickly becoming a necessity in the battle against climate change. According to the Intergovernmental Panel on Climate Change (IPCC), simply lowering our carbon emissions is no longer enough to avoid the worst effects of global warming. The IPCC report suggests that over 100 gigatons of carbon need to be removed from the air over the 21st Century to control the earth's rising temperatures (IPCC 2021).

Natural strategies to capture carbon include planting trees and using soil to store carbon. More efficient engineering strategies include *direct air capturing* and *carbon capturing*. Direct air capture filters build up carbon directly from the atmosphere. There are about 15 direct air capturing plants in the world. Carbon capture takes new carbon dioxide emissions

out of the air at the source. Since the removal process is currently expensive (ranging from \$300–\$800 per metric ton), many companies must sell the carbon dioxide. This can create counter-productive results that encourage oil companies and the use of gas vehicles. Carbon removal is most effective when the carbon is permanently stored underground. Investing in these technologies and encouraging significant government funding for carbon removal infrastructure is essential for reaching the targeted 100 billion tons of carbon removal by the end of the century.

8.3 Precedents

The following resources and examples can be used to set a precedence for air quality and developing resiliency:

Glumac Shanghai Office:

<https://www.terrabinbrightgreen.com/wp-content/uploads/2016/11/Glumac-Shanghai-Office-Fall-2016.pdf>.

Delhi Pollution Control Committee Head Office, by M:OFA Studios:

<https://www.archdaily.com/292947/office-complex-for-delhi-pollution-control-committee-proposal-mofa-studios>.

AirBubble Playground / ecoLogicStudio:

https://www.archdaily.com/963541/airbubble-playground-ecologicstudio?ad_source=search&ad_medium=search_result_projects.

Sino Green and Arup City Air Purification System:

<https://www.arup.com/news-and-events/outdoor-air-purification-system-debuts-in-beijing>.

Common Air-Rea Cloud Floor:

https://www.archdaily.com/966163/common-air-rea-cloudfloor?ad_source=search&ad_medium=search_result_projects.

Are Living Walls the Key to Cooler Cities?

<https://www.forbes.com/sites/jamiehailstone/2021/07/23/are-living-walls-the-key-to-cooler-cities/?sh=5088bd1b3f6a>.

The world's biggest plant to capture CO₂ from the air just opened in Iceland

<https://www.washingtonpost.com/climate-solutions/2021/09/08/co2-capture-plan-iceland-climeworks/>.

9 Energy

According to the [WBDG](#), “buildings use 36% of America's overall annual energy consumption, and 65% of the electricity demand.” Power outages have become increasingly common as demand rises, during extreme weather disasters (storms, floods, hurricanes, tornadoes), and rising average temperatures because of climate change.

In terms of energy resilience, It is important to find ways to reduce the load on the electrical grid, combining the use of renewable energy sources and designing buildings that are more energy efficient.

Each climate zone has different design approaches and considerations. There are a [collection of design guides](#) and case studies available for each of the different climate zones (DOE, n.d.).

9.1 Resources

Power outage tracking in real-time:

<https://poweroutage.us/area/regions>.

Major power outage events tracked:

<https://poweroutage.us/about/majorevents>.

Example of Texas winter storm event in 2021:

https://twitter.com/PowerOutage_us/status/1364366650393452544.

ASHRAE 90.1 climate zone map:

<https://www.greenbuildingadvisor.com/article/updated-climate-zone-maps-reflect-warming-trend>.

OpenEI—ASHRAE climate zones defined per county with energy resources:

https://openei.org/wiki/Category:ASHRAE_Climate_Zones.

Sun angles per location:

<https://susdesign.com/sunangle/>.

Building America Solution Center—optimized climate solutions:

<https://basc.pnnl.gov/optimized-climate-solutions>.

Building America—guide to determine climate regions by county:

https://www.energy.gov/sites/prod/files/2015/10/f27/ba_climate_region_guide_7.3.pdf.

Guide and case studies for hot-dry and mixed-dry climates:

<https://www.energy.gov/eere/buildings/guides-and-case-studies-hot-dry-and-mixed-dry-climates-0>.

Building America US Department of Energy (DOE)—best practices for hot-dry and mixed-dry climates:

<https://www.nrel.gov/docs/fy05osti/38360.pdf>.

Guides and case studies for marine climates:

<https://www.energy.gov/eere/buildings/guides-and-case-studies-marine-climates>.

Builders Challenge Guide to 40% whole-house energy savings in the marine climate:

https://www.energy.gov/sites/default/files/2013/11/f5/marine_40_guide.pdf.

Guides and case studies for cold and very cold climates:

<https://www.energy.gov/eere/buildings/guides-and-case-studies-cold-and-very-cold-climates>.

Guides and case studies for mixed-humid climates:

<https://www.energy.gov/eere/buildings/guides-and-case-studies-mixed-humid-climates>.

Guides and case studies for hot humid climates:

<https://www.energy.gov/eere/buildings/guides-and-case-studies-hot-humid-climates>.

HVAC design for hot humid climates:

<https://www.wbdg.org/resources/hvac-system-design-humid-climates>.

9.2 Techniques

9.2.1 Considerations

According to [the 2021 Whole Building Design Guide](#), energy efficiency includes some of the following techniques:

1. Reduce the heating, cooling, and lighting demand through passive strategies such as climate responsive design, daylighting, and conservation practices.
2. Specify efficient HVAC and lighting systems that consider part-load conditions and utility interface requirements.

3. Employ renewable energy sources such as solar heating for hot water, PVs, geothermal space heating, and groundwater cooling, sized for the reduced building loads.
4. Optimize building performance by employing energy modeling programs during design.
5. Optimize system control strategies by using occupancy sensors, carbon dioxide sensors, and other air quality alarms during operation.
6. Monitor project performance through a policy of commissioning, metering, annual reporting, and periodic recommissioning.
7. Consider retrocommissioning of buildings which were never originally authorized.
8. Integrate water saving technologies to reduce the energy burden of providing potable water and providing hot water.

Apply this process to the reuse, renovation or repair of existing buildings as well.

9.2.2 Technology and equipment

9.2.2.1 Generators

Generators are a useful source of backup power. Typically, they are powered with diesel and natural gas. However, standalone generators [cannot accommodate the inevitable changes the military's electric power needs](#) (Marqusee et al. 2017). They are hardwired to the buildings that they support. Moving them to a new location is expensive and time-consuming. It would require decommissioning, transportation, and recommissioning.

[Solar generators](#) should be considered, which are not actually generators, but solar systems with battery storage (SolarReviews 2022). These can provide reliable access to energy without having to worry about pollution, noise, or fuel costs like conventional gas generators. The panel turns sunlight into electricity that is stored within the portable battery storage systems. One-thousand watt of solar panels with a battery capacity of 2,000 watt hours, with a built-in inverter and charge controller—when the sun is shining—can run electronic devices in as little as four hours. Additionally, these systems can be stored with other batteries.

9.2.2.2 *Early design energy analysis using building information modeling (BIM)*

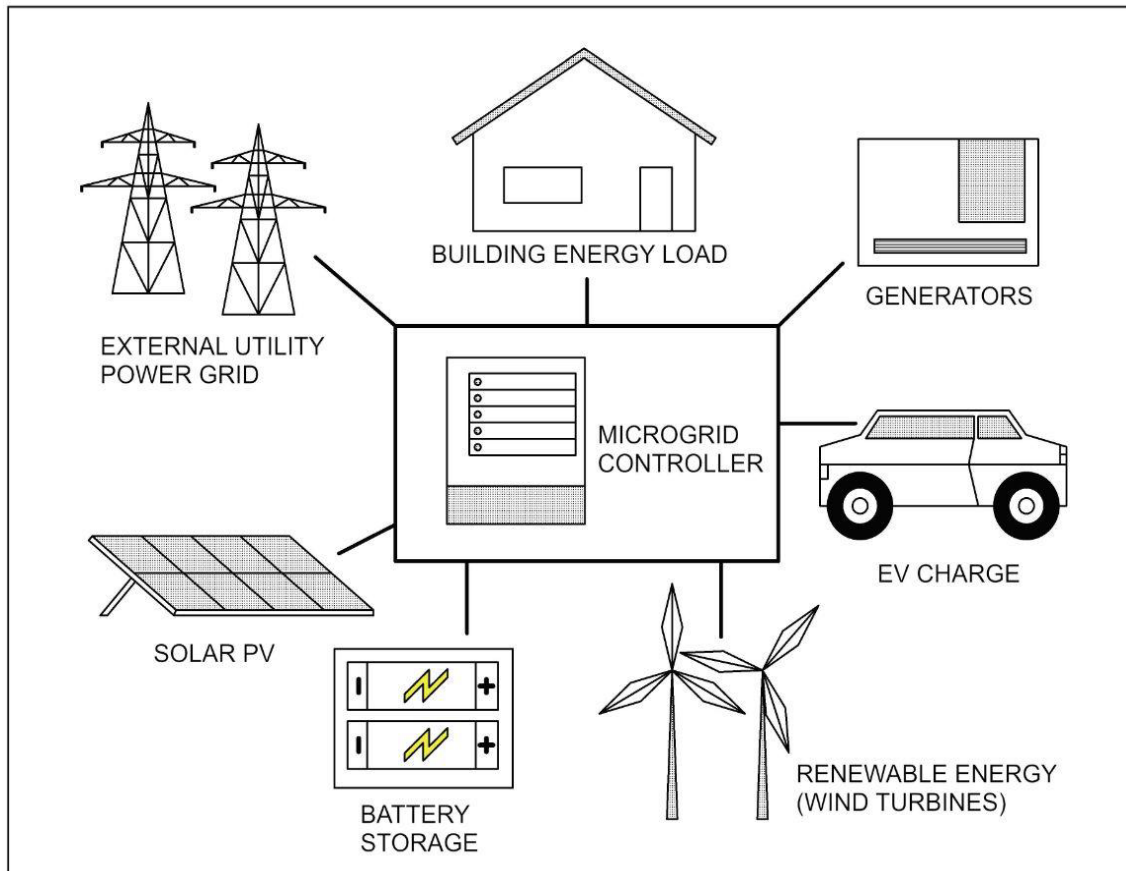
Building information modeling (BIM) energy analysis models during the schematic phase can optimize building design to take advantage of sun orientation.

9.2.2.3 *Microgrid*

Microgrids are a [localized group of electricity sources](#) and loads (solar, wind, fuel, and batteries) that normally operate connected to the power grid (Burke 2018). However, they can go on *island mode* and operate from stored power, which helps maintain power critical infrastructure during emergencies.

Smart grids are electrical grids that include smart meters, smart appliances, renewable energy resources, and energy efficient resources. This technology can automatically detect, isolate, and reroute power when problems occur. This reduces the number of outages, decreases the duration of outages, and helps restore power within minutes. See Figure 17.

Figure 17. How microgrids could operate on “island-mode” with enough renewable energy.



MICROGRIDS

9.2.2.3.1 Why microgrids may be preferable to stand-alone generators

- **Efficient sizing:** a microgrid shares resources across a large number of buildings on an installation which reduces the volume of power currently needed.
- **Maintainability:** a microgrid relies on a few, large generation units that often have standardized features, making it far easier and less expensive to maintain.
- **Reliability:** a microgrid can readily provide a high level of reliability because the networked structure ensures that if any single generation asset fails, another one can instantly take its place.
- **Flexibility:** microgrids are networked, they can respond to changes in electricity needs at no cost as missions change and requirements evolve. Unlike standalone generators, microgrids can integrate the power from renewable energy sources.

- Coverage: a microgrid is sized to meet the annual critical peak loads of a group of buildings on a base load, excess generation is almost always available and can serve any load to which the microgrid is connected, including those loads whose priority falls between “critical” and “non-critical.”
- Distribution needs to be reliable.
- Cost less to assure power than stand-alone generators (Marqusee et al. 2017).

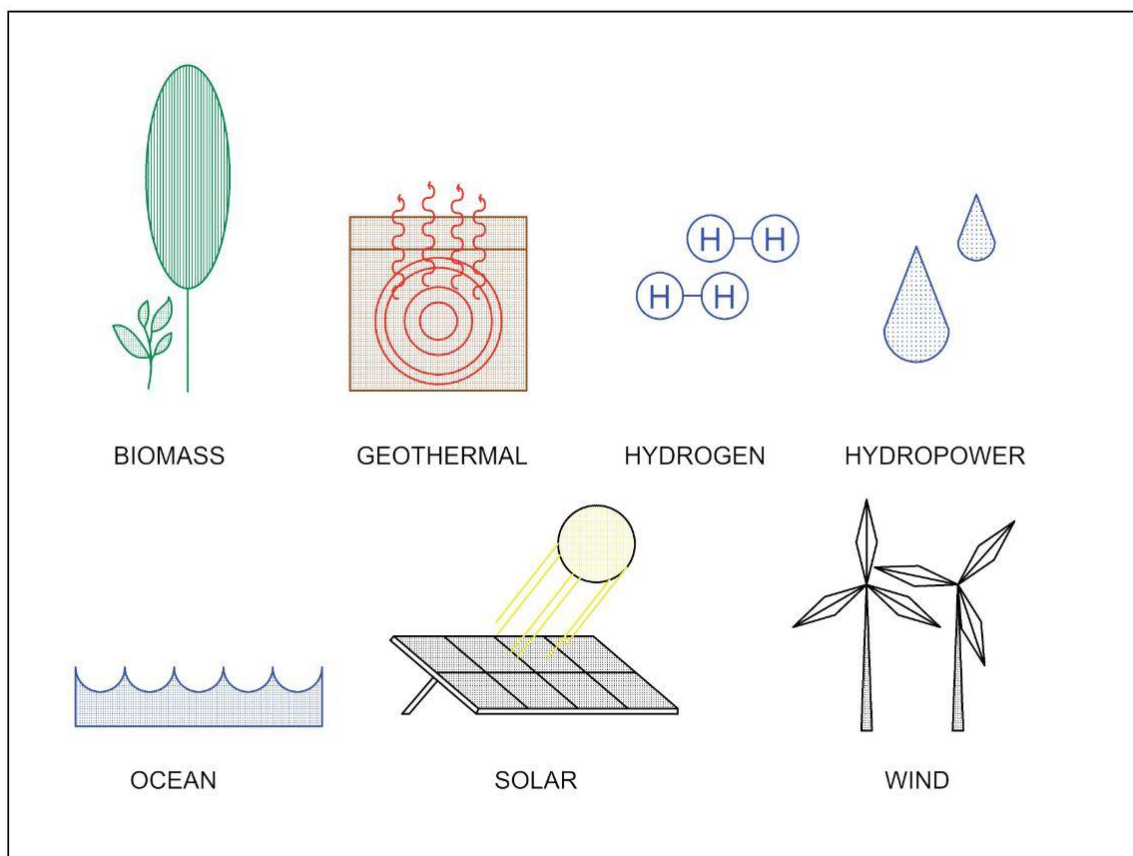
9.2.2.4 *Transportation*

There are [developments in transportation](#) that use more sustainable fuels (NREL, n.d.). One of the most common technologies currently are electrical vehicles; batteries are developed to be more efficient. There are also cars being developed that allow for back charge or [vehicle-to-grid](#) in the case of emergency demand (Wikipedia 2023b).

9.2.2.5 *Alternative energy sources*

There are various ways to produce energy that does not involve the typical process of burning fossil fuels. See Figure 18 for a diagrammatic summary and read the following sections for a quick overview of the alternative energy sources currently implemented and researched.

Figure 18. Renewable energy types.



RENEWABLE ENERGY

9.2.2.5.1 Biomass

Energy that is [derived from plants and plant-derived materials](#) (NREL, n.d.). Wood is the largest biomass energy resource today. Some other examples are algae, organic components of municipal and industrial waste, paper mill residue, lumber mill scraps, and fumes from landfills. Biofuels, such as ethanol and biodiesel are created by converting biomass into liquid fuel.

9.2.2.5.2 Geothermal

Energy that is derived [from the heat from the earth](#) (NREL, n.d.). This can be used for hot water, heating buildings, and generating electricity. Utilities can use the hot water and steam from reservoirs to drive generators and produce electricity. Some other applications of geothermal energy include heat pumps, and direct hot water from the earth. The Missouri University of Science and Technology Campus in Rolla, Missouri converted a

[69 year old coal plant to a Geothermal Energy](#) System (Missouri University of Science and Technology, n.d.).

9.2.2.5.3 Hydrogen

Energy that stores and [transports energy produced](#) from other resources (NREL, n.d.). It is produced as a byproduct of other sources of energy, meaning that it is an energy carrier. When combined with oxygen in a fuel cell, hydrogen produces heat and electricity with only water vapor as a by-product. More development is needed in terms of production and storage technologies in order for this to become cost-effective and feasible.

9.2.2.5.4 Hydropower

Energy that is [captured from flowing water](#), using dams or other kinds of structures that alters the flow of water and converting kinetic energy into electricity (NREL, n.d.). Hydropower costs less than most other energy resources, about 7% of the US's electricity is produced in this way.

[Microhydropower systems usually generate up to 100 kilowatts of electricity](#). They can be implemented by small businesses and homeowners (Energy Saver, n.d.).

9.2.2.5.5 Ocean

Energy that is [produced from the ocean's tidal waves](#), including thermal and mechanical energy (NREL, n.d.). Hydrokinetic power could be converted into electricity. There are lots of opportunities here, as the earth is covered with about 71% ocean water.

9.2.2.5.6 Solar

Energy that is converted from thermal [energy from the sun](#) (NREL, n.d.). Because sunlight is so plentiful, solar photovoltaics (PV) are the most common use of solar energy. It is used for heating and cooling buildings. Solar energy could also be used for water heating. The most common use of solar energy is through a rooftop panel system.

DoD bases, which occupy 28 million acres of land, are well situated to support solar, and other kinds of renewable energy sources. [A year long study](#) looked at seven installations in California and two in Nevada and found that even though military activities and the presence of endangered

species made only 4% of the area solar-compatible, the amount was enough to support the generation of 7,000 MW of solar energy, the equivalent amount of seven nuclear power plants (Marqusee et al. 2017).

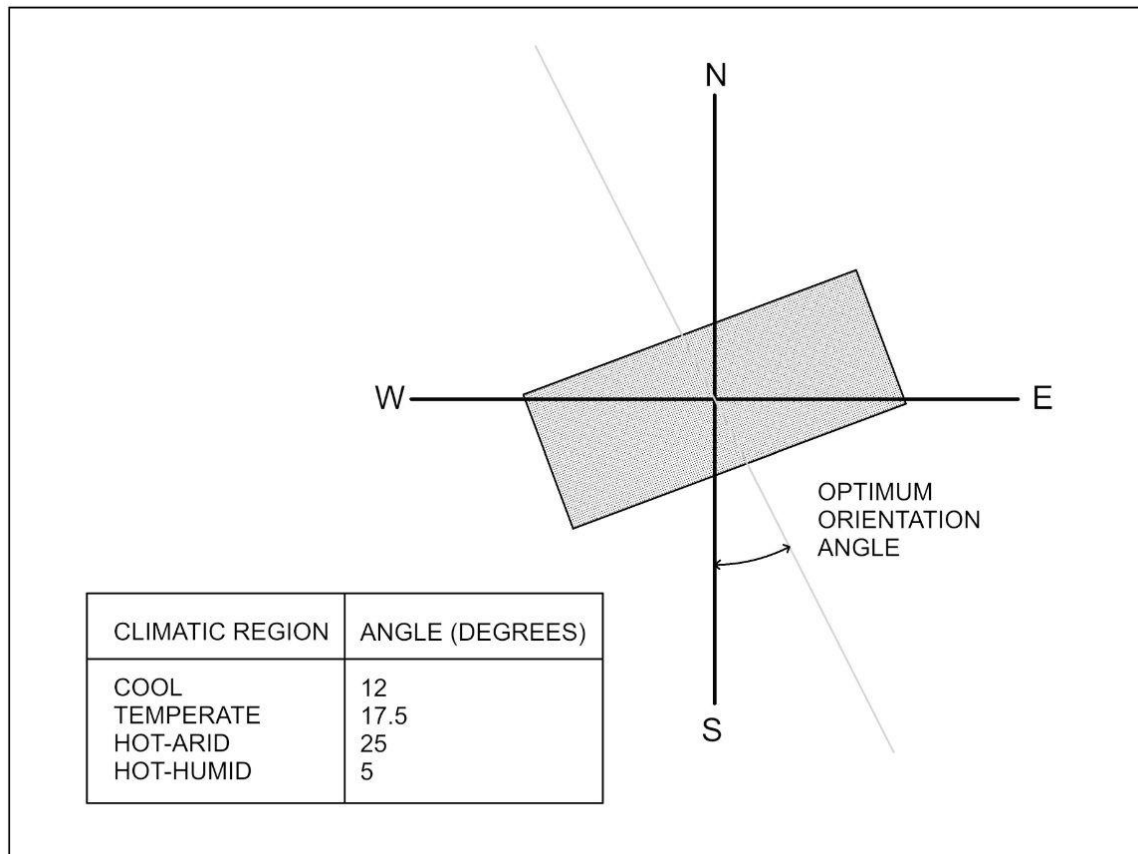
9.2.2.5.7 Wind

Energy that is [produced from wind](#), which is caused by the uneven heating of the earth (NREL, n.d.). One of the most common technologies using this source of energy are wind turbines, which generates power from kinetic energy produced from the spinning of the blades.

9.2.3 Climate responsive design

The design of a building should take advantage of opportunities and mitigate challenges that a climate zone has. One of the simplest ways to optimize heating and cooling loads is orienting the building in the correct direction. Resiliency appears in the initial preparation and design of a building, reducing the amount of energy needed and taking advantage of passive systems that are often more reliable. See Figure 19 for more information. The following sections will offer an overview of design principles tailored to some climate zones.

Figure 19. Optimum building orientation.



OPTIMUM BUILDING ORIENTATION

9.2.3.1 Hot-humid

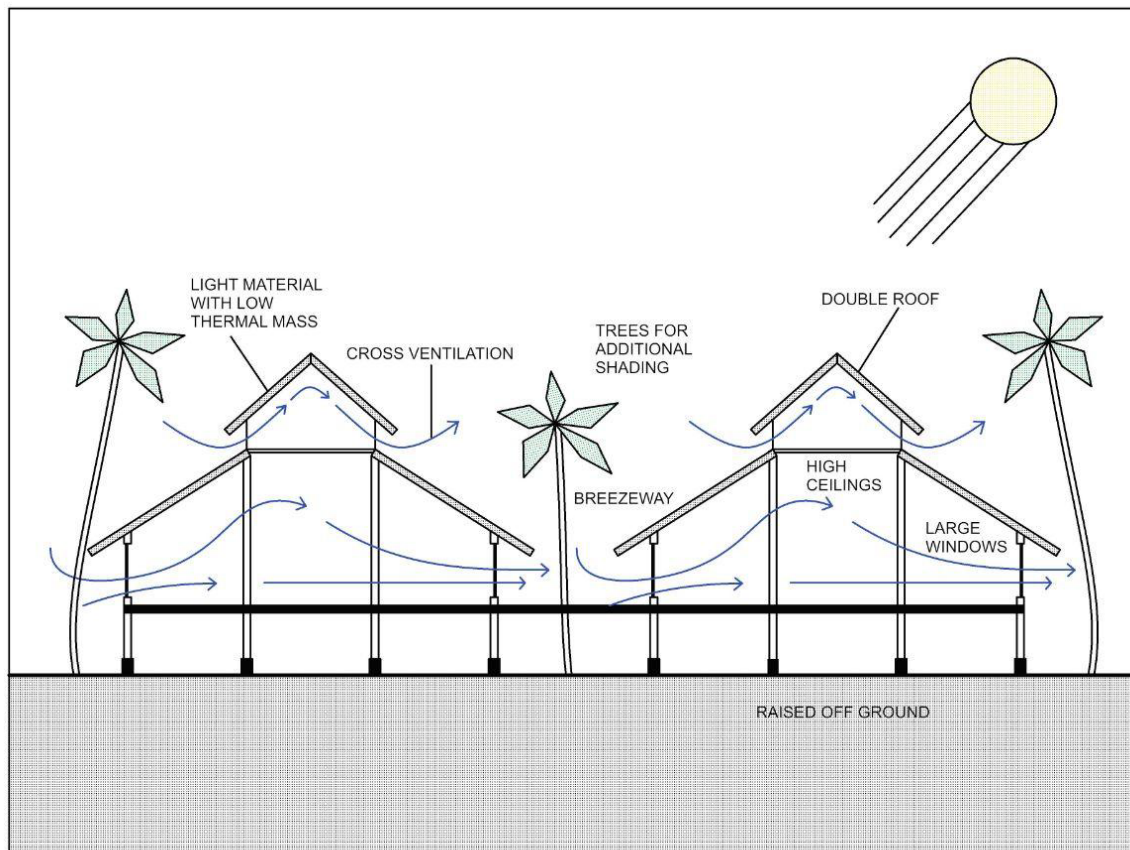
This is the most difficult [climate zone to design](#) without mechanical cooling (DOE, n.d.). Looking back at the construction methods of indigenous architecture and vernacular is recommended to design buildings that are suitable for this climate zone. See Figure 20 for a diagram in the typical building form for this climate zone.

- Building form:
 - Compact building forms with a low surface area to volume ratio—circular or square building
 - Narrow floor plan with porches and breezeways
 - High ceilings
 - Raised off the ground to take advantage of prevailing winds and minimize moisture retention and insects and pests

- Orientation of building:
 - Orient building along the long axes in the east-west direction.
 - Orient building 5 degrees east of south axis
- Ventilation:
 - Use cross ventilation to cool down buildings; orientation should allow for [oblique winds between 30 and 120 degrees to the wall](#) (Chitnis 2022)
 - Attic spaces can be used to decrease solar heating on roofs
- Windows:
 - Large windows for cross ventilation, but should be shaded properly
 - Unshaded windows should be limited to 15% of the area of the facade
 - External shading devices should be designed according to the sun path
- Landscaping:
 - Deciduous trees planted in south-west and west side can help provide shade in summer and winter
 - Evergreen trees in north and north-west side can provide shade year-round
- Implementing innovative daylighting systems:
 - Examples include the light pipe, which transports natural or artificial light into buildings
- Courtyards:
 - Allow for cross ventilation and wind
 - Additional trees in courtyard can provide shade for building occupants and more

- Room arrangements:
 - Design programmatic functions according to orientation
 - Rooms on western side are cooler in the morning and hotter in the afternoon, good for things like storage rooms, and kitchens
 - Rooms on the east side tend to be hotter in the morning and cooler in afternoon, good for things like bedrooms
 - Northern and southern rooms stay cooler if shaded properly
- Roof:
 - Double roof allows warm air building between the roof structure to escape and reduces the cooling loads necessary for building
- Green walls:
 - Provide protection from solar radiation, reduce glare, sound absorption, filters air, and stabilizes the humidity levels
- Material:
 - Building materials should minimize thermal mass so that the building does not store heat
 - Light colors

Figure 20. Example of a typical building designed with passive techniques for hot-humid climates.



HOT HUMID CLIMATES

9.2.3.2 *Mixed-humid*

- Roof:
 - Should be designed to take advantage of solar panels, tilt angle of 30 degrees facing south direction
 - Overhangs, porches, awnings, trellises but account for differences in sun angles, elevation, window height and width, wall height above window, and amount of shading desired according to time of day and time of year
 - Use metal roof to prevent moss growth in humidity
- Windows:
 - Should be selected to manage the quantity of heat loss and solar gain, indicated by the U-value solar heat gain coefficient

- Trees:
 - Reduce cooling requirements when located on the south, east, and west side of buildings.
 - Block low-angle, morning and late afternoon, peak solar-gain sun
 - [Medium and large trees should be planted 16 to 22 feet from the side of the house, smaller trees can be planted 10 to 16 feet from the side of the house](#) (Baechler et al. 2001)
 - Rule of thumb is that any potential shading structure should be twice as far away from the solar equipment as the structure is tall
- Ventilation:
 - Exhaust fans, ceiling fans remove moisture inside building and ensures more air
 - Providing a ventilation space behind exterior wall cladding allows the material to dry out and prevents the moisture from contaminating housewraps, sheathing, or other wall components

9.2.3.3 Hot-dry and mixed-dry (arid)

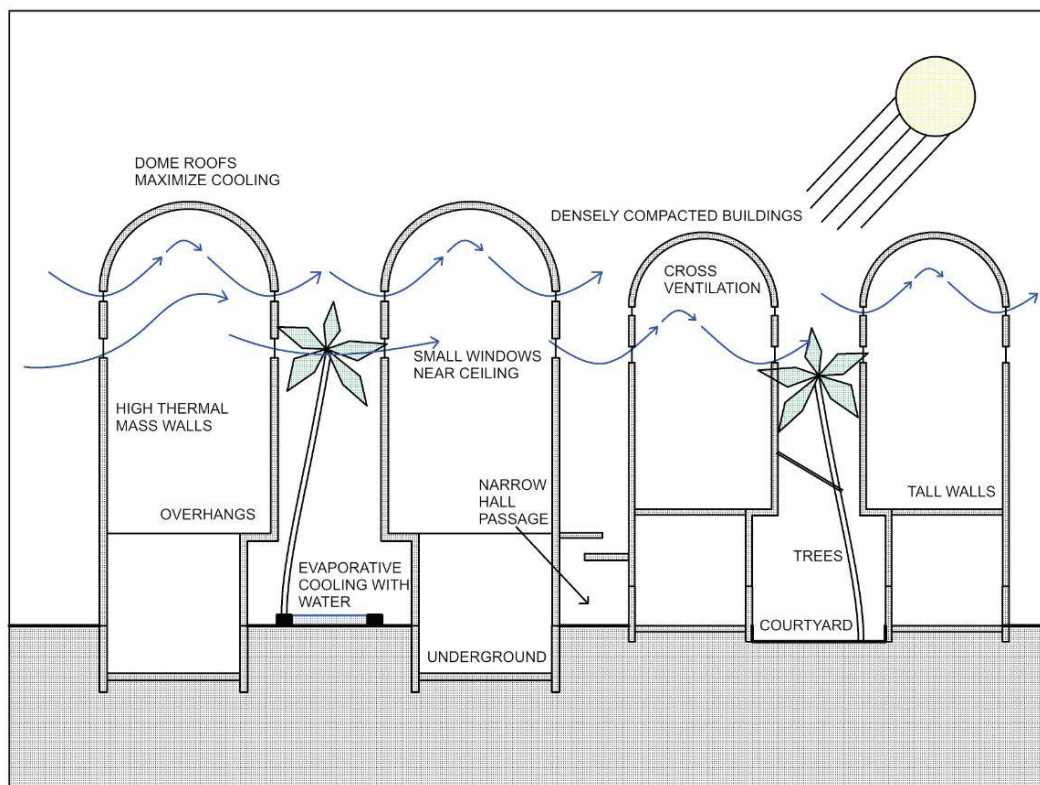
Shading from [direct sunlight](#) is necessary (DOE 2014). See Figure 21 for a diagram in the typical building form for this climate zone.

- Orientation:
 - Orient building 25 degrees east of south axis
- Density:
 - Buildings are connected together and protected from sun with covers
 - Compact building forms with smallest surface area possible to volume
- Surrounded urban space and tall walls:
 - Spaces are surrounded by tall walls to protect from hot and sandy winds
 - Walls made of material with high thermal mass, allowing for thermal lag at night
 - Wall material are [kept light in color](#) to reflect thermal energy and provide more daylight (Varzaneh et al. 2014)

- Courtyard:
 - Usually have internal courtyards for outdoor space
 - Narrow courtyards to maintain shaded area when it is hot, planted with trees and other plants to provide shading and evaporative cooling benefits
 - Sometimes paired with a water pool in courtyard to help cool with evaporation
 - Roof ponds for one- or two-story buildings can provide evaporative cooling and high thermal mass
 - Night ventilation
- Roofs:
 - Tall roofs that provide shade
 - Air vent elements
 - Dome roofs allow for minimized radiant heating and maximize cooling
- Windows:
 - Kept small and located in the upper parts of walls near ceiling
 - Windows kept out of external walls but plenty on the walls facing an internal courtyard
 - Avoid placing many windows on east and west exterior facade
 - Provide shade for all openings
- Material:
 - Materials in high thermal mass to take advantage of wide variation of temperatures between day and night—the heat stored during the day will be released at night
 - Light colors
- Narrow irregular passages
 - Alleys are not straight, to provide shade in most times a day

- Sabat and Fina
 - [In traditional Iranian architecture](#), sabat is designed to protect from direct radiation, modulate temperature, and create entrances that are more climatically comfortable
 - Fina are zones along the street wall of a building where balconies, downspouts, and other protruding features, that do not impede circulation
 - Sabat is a structure built between opposite buildings on both sides of a narrow street (Moossavi 2014)
- Wind towers and basements
 - [Wind catcher](#) allows for ventilation in the summer
 - Underground space is found in traditional mosques, and schools in ancient Persia, known as the Shabestan; they are used with wind towers (Behbood et al. 2010)

Figure 21. An example of a typical building form for hot-arid climate zones.



HOT ARID CLIMATES

9.2.3.4 [Marine](#)

The [marine climate](#) has mild temperatures and moist conditions, found along the coast (Baechler et al. 2010). Buildings in marine climates are faced with high levels of moisture, often in the form of rain, fog, or snow. The region is vulnerable to frequent precipitation, high winds, seismic events, and forest fires.

- Orientation:
 - The best orientation would be to face the building's long side directly into the sun to the south
 - It can be oriented up to 30 degrees away from due south and lose only 5% of the potential heating savings
- Fenestration:
 - South-facing window area 8 to 10% of floor area, the building can be called *sun tempered*
 - Window area of 15 to 20% of floor area would be called a true passive solar home; requires thermal storage mass and summer shading to mitigate summer heat gains
- Overhangs:
 - Roofs should be designed to shade windows
 - Protection from rain, hail, and the effects of overheating and UV radiation
- Material:
 - Water resilient materials such as metal, glass, and concrete
 - Vapor retarders and vapor barriers are a must in building system
 - Controlled air movement is necessary
 - Providing ventilation space behind exterior wall cladding allows the material to dry out and prevents the moisture from contaminating housewraps, sheathing, or other wall components
 - Pest control from termites
 - Drainage gaps

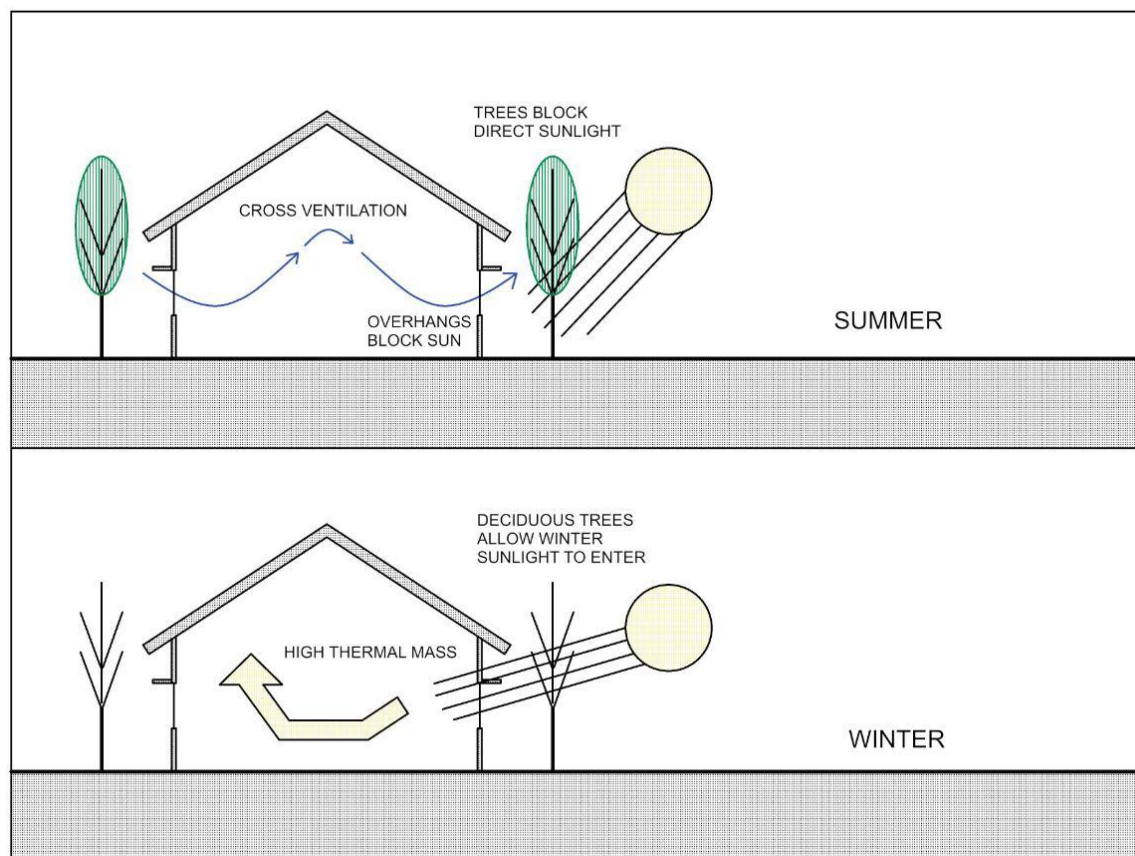
- Foundations:
 - Controlling moisture and having ventilation to prevent mold
 - Crawlspace and attics can be used for ventilation
 - Control liquid water in foundations

9.2.3.5 *Temperate*

Heat loss during the winter is significant, but the summers are also very warm; it is important to design buildings in temperate zones to be adaptable to both apparent climates during the winter and the summer. See Figure 22 for a diagram in the typical building form for this climate zone.

- Orientation:
 - Orient building 17.5 degrees east of south axis
 - Minimized northern exposure
 - Winter winds blocked to reduce heat loss
 - Orient building to maximize southern exposure for solar heat gain
- Shape:
 - Rectangular building shapes with long direction oriented generally along the east-west axis and facing slightly to the east
- Shading:
 - Deciduous trees and mechanical shading devices like awnings to protect from unwanted heat during the winter on the Southern facade
 - East and west windows should be shaded with vertical louvers
- Ventilation:
 - Provide nighttime ventilation for exhausting hot air
 - Solar heating both active and passive works well

Figure 22. How temperate climates could benefit from proper landscaping and shading.



TEMPERATE CLIMATES

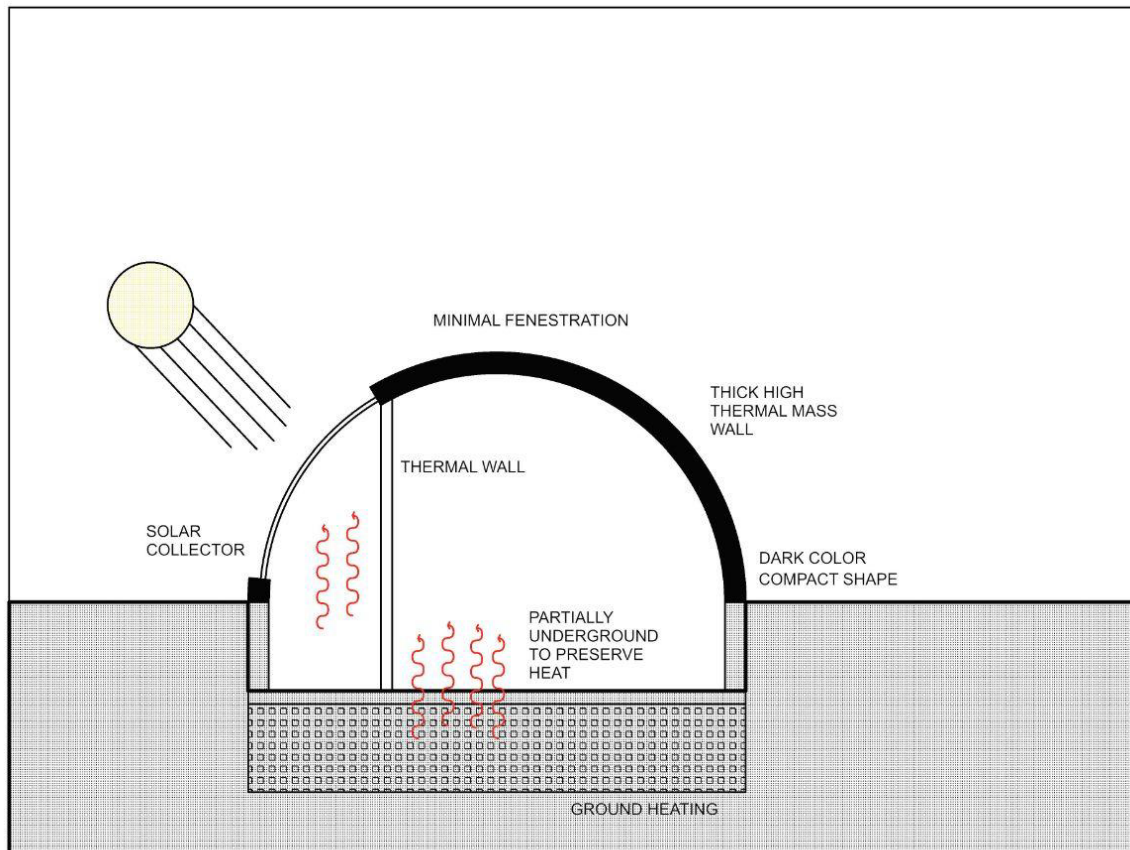
9.2.3.6 Cold and very-cold

Minimize the exposed surface area to reduce the heat loss in low temperature climates. See Figure 23 for a diagram in the typical building form for [this climate zone](#) (DOE, n.d.).

- Orientation:
 - Northern exposure minimized
 - Orient building 5 degrees east of south axis
- Heating:
 - Landscaping and building design should block winter winds
 - Passive solar heating is usually not appropriate, mechanical heating and active solar heating are needed

- Fenestration:
 - Minimize amount to conserve heat
 - Minimize northern doors
 - Large windows facing south, small windows facing east and west, and minimal windows facing the north orientation
 - Entries should have air locks
- Shape:
 - Compact, small, smallest surface area possible relative to volume
 - Cubical shape
 - Built partially underground
- Material:
 - Darker color to absorb heat
 - Materials that have high thermal mass, such as brick, masonry, and concrete

Figure 23. Cold climates designs to conserve energy.



COLD CLIMATES

9.2.4 [2015 International Energy Conservation Code \(IECC\) commentary \(2015\)](#)

It might be helpful in looking into how each city (representative of different climate types) designs buildings to work with the climatic conditions. These climate zones are defined by ASHRAE 90.1 climate zones. See Table 6.

Table 6. IECC (International Energy Conservation Code) representative cities for climate types.

Zone Number	Description	Example City
1A	Very Hot-Humid	Miami, FL
1B	Very Hot-Dry	Does not exist in the U.S.
2A	Hot-Humid	Houston, TX
2B	Hot-Dry	Phoenix, AZ
3A	Warm-Humid	Memphis, TN
3B	Warm-Dry	El Paso, TX
3C	Warm-Marine	San Francisco, CA
4A	Mixed-Humid	Baltimore, MD
4B	Mixed-Dry	Albuquerque, NM
4C	Mixed-Marine	Salem, OR
5A	Cool-Humid	Chicago, IL
5B	Cool-Dry	Boise, ID
5C	Cool-Marine	Does not exist in the U.S.
6A	Cold-Humid	Burlington, VT
6B	Cold-Dry	Helena, MT
7	Very Cold	Duluth, MN
8	Subarctic	Fairbanks, AK

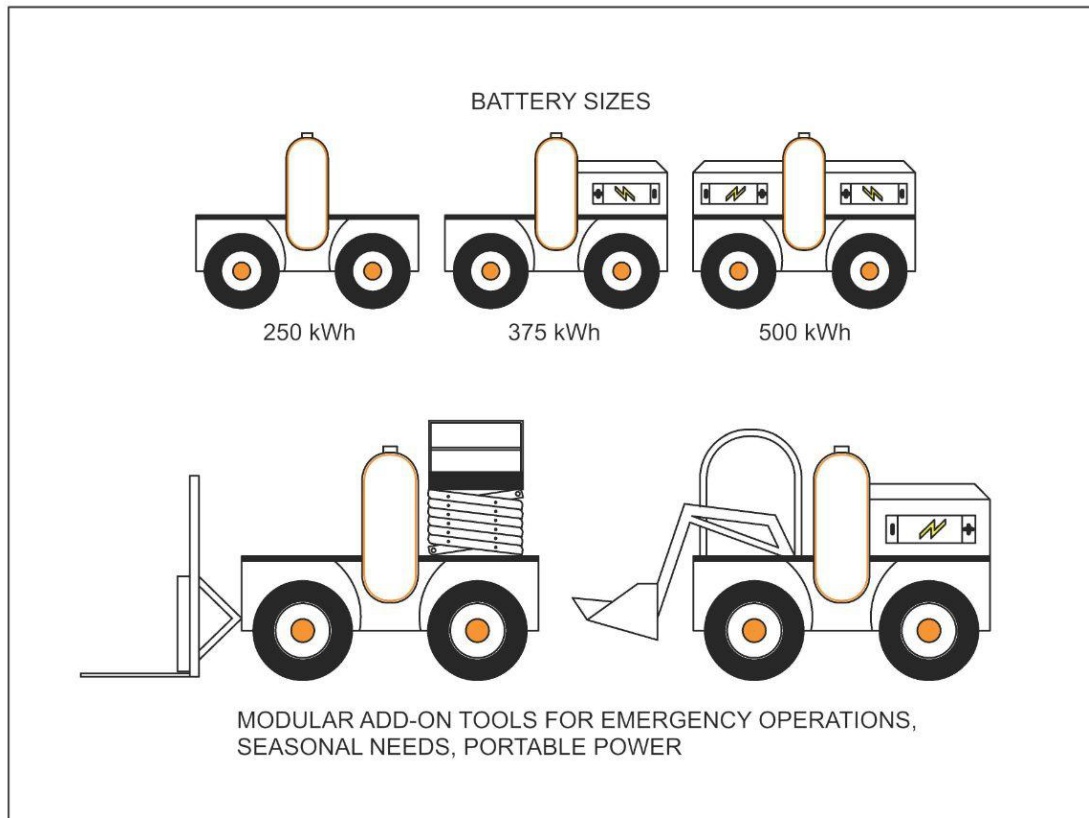
9.3 Precedents

9.3.1 DANNAR 4.00

[DANNAR Mobile Power Stations](#) could replace many single-use work vehicles (DANNAR, n.d.). It comes standardly with 125 BMW i3-Li-ion batteries that could be upgraded to a total of 504 kWh of on-board electricity. It can be powered without an operator. It is used to transport and export power for increased energy resiliency through mobile micro-grids. Solar

charging stations can be integrated to provide for extended energy independence during emergency or rescue operations. See Figure 24.

Figure 24. DANNAR 4.00 Modular Build options with detachable parts.



DANNAR 4.00

9.3.2 Con Edison climate change implementation plan

After Hurricane Sandy in 2012, [Con Edison](#), one of the largest investor-owned energy companies in the United States decided to invest \$1 billion over four years for the following improvements (Seidel and Zamuda 2018):

- strengthen flood barriers
- make equipment submersible
- raise or relocate critical equipment
- reconfigure networks for greater redundancy and flexibility
- replace vulnerable overhead lines with underground infrastructure
- expand their use of monitoring sensors, switches, and related smart grid technologies
- use the current FEMA 100 year flood maps plus three feet as their new design standard

Con Edison Climate Change [Vulnerability Study](#) (Con Edison 2019) investigated the following:

- Average and maximum air temperatures are projected to increase
 - New York City, New York—up to 23 days per year in which max temp exceeds 95°F by 2050 relative to 4 days. Heat waves with 3 or more days when avg temp over 86°F projected to occur 5–14 times per year by 2050 and 2080 relative to 1 heat wave every 5 years historically
 - Temperature variable (Combining effect of air temp and relative humidity)
 - Projected more frequent heavy precipitation
 - Sea level rise, thus higher probability of coastal flooding
 - More frequent extreme weather events
- Con Edison worked to introduce processes to address this consideration—[absorb: temperature, temperature Variable \(TV\), hurricanes, heat waves, precipitation](#) (Con Edison 2021)
 - Utility partnering with city to prevent trees from interfering with overhead power lines
 - New technology to boost communication from customer to utility line to stay informed, report damages through mobile app
 - Smart metering allows real-time information on outages. Sending resources to areas that actually need it

10 Waste

Buildings and people produce waste that often end up in landfills. The problem with landfills is that the [toxins within the waste](#) could end up leaching into groundwater and soils, polluting resources that we need in the future (Environment Victoria 2013). Organic wastes in landfills are often compacted and covered, causing it to decompose anaerobically; this means that excess methane is produced. This contributes to global warming in addition to being highly flammable.

10.1 Resources

Waste management:

<https://www.wm.com/us/en/inside-wm/social-impact/education-resources>.

Reinvent the toilet:

<https://www.gatesfoundation.org/our-work/programs/global-growth-and-opportunity/water-sanitation-and-hygiene/reinvent-the-toilet-challenge-and-expo>.

UFC 3-250-07 *Standard Practice For Pavement Recycling*:

<https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-250-07>.

Guide for Developing Integrated Solid Waste Management Plans at Army Installations:

https://phc.amedd.army.mil/PHC%20Resource%20Library/FINAL_TG_197_November_2013.pdf.

10.2 Techniques

10.2.1 Rethink reduce, reuse, recycle (The Three Rs)—questions to ask

Systems should be created to reduce the number of things automatically sent to the landfill. This includes a dedicated donation area for household items to be donated to other people. Doing a primary filtering could reduce the amount of waste (Rinalducci 2023). See Table 7.

Table 7. Expanding The Three Rs to further questions.

Recycle	What are things that can be put back into the loop so new resources are not consumed?
Refuse	Is it needed?
Reduce	Is that much necessary? Can energy and water use be limited?
Reuse	What are new ways to prolong the life of the object?
Repair	Is the object fixable rather than being thrown away?
Regift	Can it be given to someone else?
Recover	Can it be upcycled it and take something old and make it anew?

10.2.2 Composting and gardening

Food waste and organic matter could be collected for composting. Dining facilities can integrate areas where food scraps and paper could be collected. The compost could go to community gardens or fed to livestock. Additionally, this would reduce the amount of organic waste going to the landfill, and thus reduce the amount of methane released into the air (Gebhart et al. 2016). See Table 8.

Table 8. Composting techniques.

—	Aerobic	Anaerobic	Vermicomposting
Location	In a bin or pile that has good air flow and circulation.	In a sealed container or pile.	In a self-contained bin.
Method	Organic materials are layered and turned routinely, allowing for more heat to be generated and has a faster decomposition time.	Organic materials are buried and layered or compressed and left to slowly compost. This is less labor intensive but a slower process.	Worms are mixed with layers of kitchen scraps. The organic material does not need to be turned and the fertilizer could be harvested for fertilizer. Little to no odor is there if supplied with enough moisture and nitrogen rich materials.
Challenges	More labor intensive and requires more space.	It takes longer, smells worse, and can contain harmful pathogens. Methane is produced.	Labor intensive and cannot be left alone.

The compost pile must be layered alternatively with brown layers of carbon-rich material and green nitrogen-rich materials.

Brown layers include twigs, straws, shredded paper, topsoil, dried leaves, clippings, and cardboard. Green layers include landscaping yard waste, kitchen scraps, food waste, grass, and leaves.

10.2.3 Composting toilets

Composting toilets are a type of toilet that treats human biological waste through decomposition. Microorganisms decompose the waste aerobically, converting waste to compost that can be used for fertilizer. See Section 3.4.2 *Bullitt Center—Seattle, Washington* for a good example of this being used in a building.

10.2.4 Converting waste to burnable fuel

An alternative to burying waste is burning it to be used as fuel. See Section 10.3.1 *Singapore Waste Management—Singapore* precedent in this section for more details.

10.3 Precedents

10.3.1 Singapore Waste Management—Singapore

Singapore's [solid waste disposal infrastructure](#) consists of four waste-to-energy (WTE) plants (NEA, n.d.). Incineration reduces the volume of solid waste by about 90%, and produces steam that runs turbine generators to generate electricity. The byproduct of the incineration is ash, which is transported to the Tuas Marine Transfer Station for disposal in the landfill.

However, it is important to note the long-term effects of incineration. While it helps reduce the volume of waste going to landfill, there are downsides to this method of disposal.

1. People are not compelled to conserve energy when they think that the energy produced by burning waste is sustainable. WTE only accounts for 3% of Singapore energy demands.
2. It discourages recycling. Most of the recycled waste is exported.
3. Resources are lost, meaning that more things are produced and consumed instead of reused or recycled.

4. It stifles innovation in waste management, while the landfill is expected to be filled by 2035.
5. Increased carbon emissions and air pollution, decreasing air quality and potentially posing health hazards.

10.3.2 PVT Land Company—Nanakuli, Hawai'i

This [landfill](#) reclaims and recycles construction and demolition debris (Waste Today Staff 2014). Each day, 1,775 tons of debris enter the facility, where 80% is recycled and more than 50% is converted into feedstock for use in renewable energy production. The fuel can be burned to generate steam for turbines in Oahu, Hawai'i's power plants or used in manufacturing processes to produce synthetic natural gas.

10.3.3 Reinventing the toilet

The Gates Foundation hosted a [competition to redesign the toilet](#) for third world countries (Gates 2012). Each team was given \$400,000 and asked to present their design at the end of the year. Questions posed by Bill Gates for the engineers were challenging,

Can you burn human excreta? Can you get energy out of it and how can you use or store that energy? How do you deal with smells as well as a flush toilet does? How do you make a complete toilet system simple, affordable, and something that doesn't need a lot of maintenance?

The [Reinvent the Toilet Challenge](#) is aimed to create a toilet that,

1. Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients.
2. Operates off-the-grid without connections to water, sewer, or electrical lines.
3. Costs less than US \$0.05 cents per user per day.
4. Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings.
5. Is a truly aspirational next-generation product that everyone will want to use—in developed as well as developing nations (Gates Foundation, n.d).

10.3.4 RTI TOWR system

Under the grants of the Reinvent the Toilet Challenge, [RTI engineered a toilet](#) that operates in a closed loop: it treats and reuses liquid, while generating power via a chemical-free combustion and electrochemical process with human feces (RTI International, n.d.).

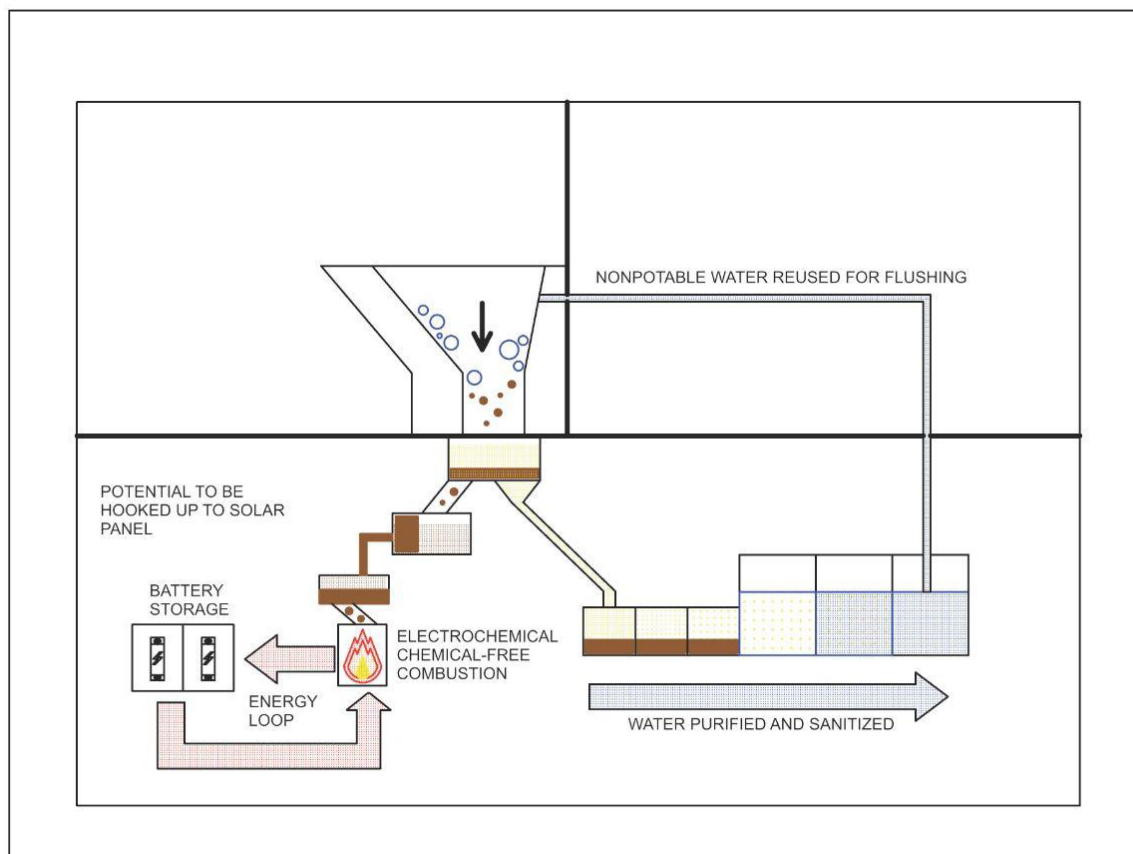
It is designed to operate off-grid—without piped-in water, a sewer connection, or outside electricity—human waste is converted into burnable fuel, stored energy, and disinfected, nonpotable water, all for an operating cost of less than US \$0.05 per day. The system runs on the equivalent power of two car batteries and in the future this could be replaced with solar energy stored in batteries.

In 2017, RTI partnered with the US Army Natick Soldier Research, Development and Engineering Center to adapt the off-grid toilet system to serve military personnel stationed at forward-operating bases, which are temporary bases without running water and electricity. TOWR, is the first system of its kind to be developed that contains no bacteria, thus it could easily be transported across international boundaries. The TOWR prototype can support 10 to 50 people and require minimal maintenance.

The use of the TOWR system means that the large number of people supporting base operations are reduced, allowing for more human resilience in military operations. Currently, human waste is trucked out of these bases, which is dangerous to the lives of those disposing of the waste. If the waste is burned on site, it is damaging to the environment.

These off-grid toilet systems could be deployed in the case of national disasters during recovery efforts after a hurricane or large storm. It can be used in refugee camps, remote locations without power supply, in construction sites, and for migrant workers. It is also useful during festivals, tourist sites, and places of large public gatherings. See Figure 25

Figure 25. RTI TOWER system.



RTI TOWER SYSTEM

10.3.5 Deconstruction of WWII era wood-framed buildings

There are case studies with lessons learned on the deconstruction of surplus buildings on seven military installations located on the [WBDG web-site](#). It has guidance on the recovery, reuse, and recycling of materials from building deconstruction.

Resilience is shown by reducing the amount of waste going to the landfill and the overconsumption of virgin material when recycled materials are conserved. Webster and Napier, the authors of the technical bulletin, stated that the demotion of the buildings on the participating installation constitutes approximately [85% of its solid waste burden](#) (USACE 2007). The salvaged materials can be a significant way to provide the installation with additional revenue from sale or reuse in future projects. See Table 9 for a list of materials that are recovered for reuse or recycled.

Table 9. Salvage and recovery patterns in demolition projects.

Materials Recovered for Reuse:	• large heavy timbers • dimensional lumber (e.g., 2 in. × 10 in., 2 in. × 8 in., 2 in. × 6 in.) • metals, structural steel • concrete • brick/masonry • wood paneling, molding, and trim • hardwood flooring • siding • cabinets and casework • electric equipment and light fixtures • plumbing fixtures and brass • windows, doors, and frames • heating ducts • architectural antiques
Materials Recovered for Recycling:	• dimensional lumber (2x4 or smaller) • gypsum drywall • carpet/carpet pad • structural concrete • rebar • brick/masonry • roofing material • insulation • ceiling tiles • glass • fluorescent tubes • scrap metal • electrical cable • copper and metal pipe

The Fort Knox Recycle Program and Directorate of Community and Family Activities “sold” the recycled rights to the apartments at an auction. See Table 10 for a list of items offered.

Table 10. Fort Knox Recycle Program items auctioned.

Electronics	Microwaves, vacuum cleaners and parts, washers, dryers, refrigerator, Frigidaire freezer, floor model television, DVD player, VCR, hot water heater, dishwashers, and three-door beer cooler.
Lighting	Light fixtures and floor lamps.
Household	Bedspreads, bed linen, towels, mini-blinds, scale, soap dispenser, and coat rack.
Furniture	Recliners, night stands, head board, chairs, dining chairs, corner restraint chairs, table, and outdoor patio furniture.
Office	Miscellaneous computer equipment, computer desks, wooden and metal desks, microfiche reader, and fax machines.
Building or Structure Supplies	Bath boards, bathtub guards, upper and lower cabinets, countertops with sinks, wood, hardwood flooring, metal shelving, and metal cabinets.

The apartments for sale could contain kitchen cabinets, stainless steel sinks, plumbing fixtures, electrical fixtures, central air and heat units, water heaters, double pane windows, doors, hard wood floors, and wood staircases. If the bidder did not purchase the entire building, the outside packages were to be auctioned off separately. Outside packages included vinyl siding, aluminum gutters and attached sheds. No structural component could be removed unless the bidder purchased the entire building.

The US Army Engineering and Support Center, Huntsville Facilities Reduction Program (FRP) and the Kansas City District finalized the deconstruction pilot project at Fort Leonard Wood, Missouri in December 2015. [The demolition project](#) cost less than \$800,000, and was able to salvage and reuse materials from three WWII era buildings (Newcomb 2015).

11 Antiterrorism

When designing buildings in the modern age where terrorism is a big concern, it is important to consider mitigation against man-made threats. The world is becoming increasingly populous; designing security into a building is a requirement to ensure the resilience of expensive buildings and the occupants inside them.

Consider how buildings could be designed to minimize infrastructural damage and protect occupants, in the event of the following:

- Bomb threats (traditionally, the dominant threat from terrorists, as it is sensational)
- Mass shootings and weapons
- Intentional vehicular collisions
- Airborne chemical, biological and radiological releases

Additionally, consider how antiterrorism measures could also help make outdoor areas more walkable, safe, and pleasing to pedestrians. [Complete Streets Design](#) prioritizes the safety of pedestrians, bicyclists, and motor vehicles; this includes things like protected bike lanes, trees planted to buffer traffic speeds, and accessible infrastructure (Aldrich 2022).

In the United States, activity spilling out onto the street was not as culturally common. However, the Covid-19 pandemic resulted in restaurants offering temporary outdoor seating in public spaces. Street performances, pop-ups, and farmer's markets are also examples of temporary architectural spaces that require consideration. It is important to protect people in occupied zones that are located adjacent to fast traffic and potential threats. Hence, antiterrorism measures and hardening protective infrastructure could benefit people in multiple ways.

11.1 Resources

USACE Center of Expertise—Protective Design Center:

<https://www.nwo.usace.army.mil/pdc/home/>.

WBDG Blast Safety of the Building Envelope:

<https://www.wbdg.org/resources/blast-safety-building-envelope>.

WBDG Security For Building Occupants and Assets:

<https://www.wbdg.org/design-objectives/secure-safe/security-building-occupants-assets>.

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<https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-340-02>.

UFC 4-020-01 *DoD Security Engineering Facilities Planning Manual*:

<https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-4-020-01>.

UFC 4-010-01 *DoD Minimum Antiterrorism Standards for Buildings*:

<https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-4-010-01>.

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<https://www.fema.gov/sites/default/files/2020-08/fema427.pdf>.

FEMA *Site and Urban Design for Security: Guidance Against Potential Terrorist Attacks*:

<https://www.fema.gov/sites/default/files/2020-08/fema430.pdf>.

The National Capital Urban Design and Security Plan:

https://www.ncpc.gov/docs/National_Capital_Urban_Design_and_Security_Plan.pdf.

Types of bollards:

<https://www.reliance-foundry.com/bollard/bollard-definition>.

11.2 Techniques

11.2.1 Site location and layout

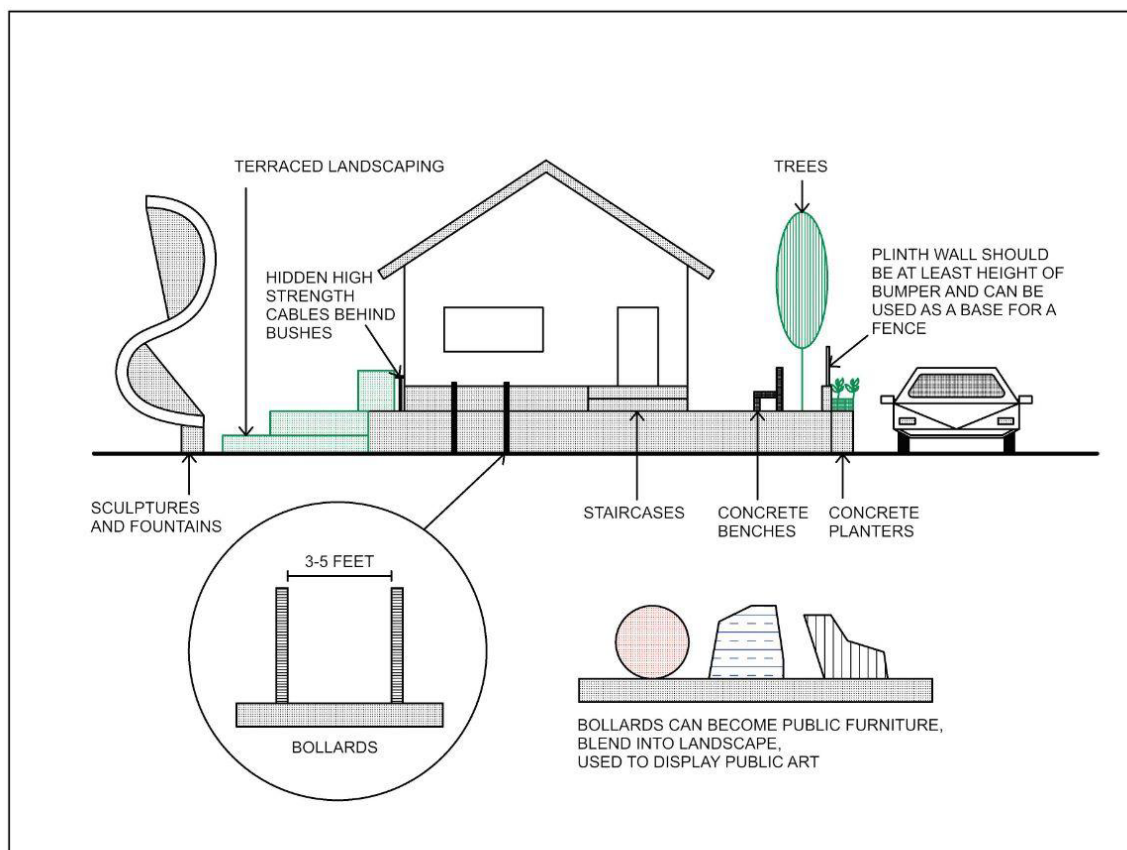
The [distance between a potential bomb threat and the building](#) that needs to be protected should be increased (Hinman et al. 2003). Security should be provided along the perimeter of the facility to protect it from vehicles and to keep all vehicles away from the building to prevent weapons carriers from gaining access.

The perimeter of the building could be pushed out to the edge of the sidewalk with bollards, planters, and other landscaping. Eliminating loading zones and closing streets could also be beneficial. The building should be placed as far away from the property line as possible. The following designs can be used in protecting a building:

- Terraced landscaping
- Fountains
- Statues
- Staircases
- Bike racks embedded in concrete
- Circular staircases and driveways
- Planters and trees that are as tall as cars or truck bumpers
- High strength cables hidden in bushes
- Place parking as far from the building as possible
- Bollards spaced 3–5 feet from each other
- Plinth wall (continuous knee wall constructed of reinforced concrete with buried foundation), could be used as a bench, a base for a fence, or wall of a planter

See the [Montgomery County Complete Streets Guide](#), which details out *Complete Streets* that are safe and pleasant (Montgomery Planning 2021), Section 11.3.1 *Making bollards aesthetically pleasing* precedent, and Figure 26 for further understanding.

Figure 26. Protection devices that could be incorporated in a typical building.



PROTECTION DEVICES

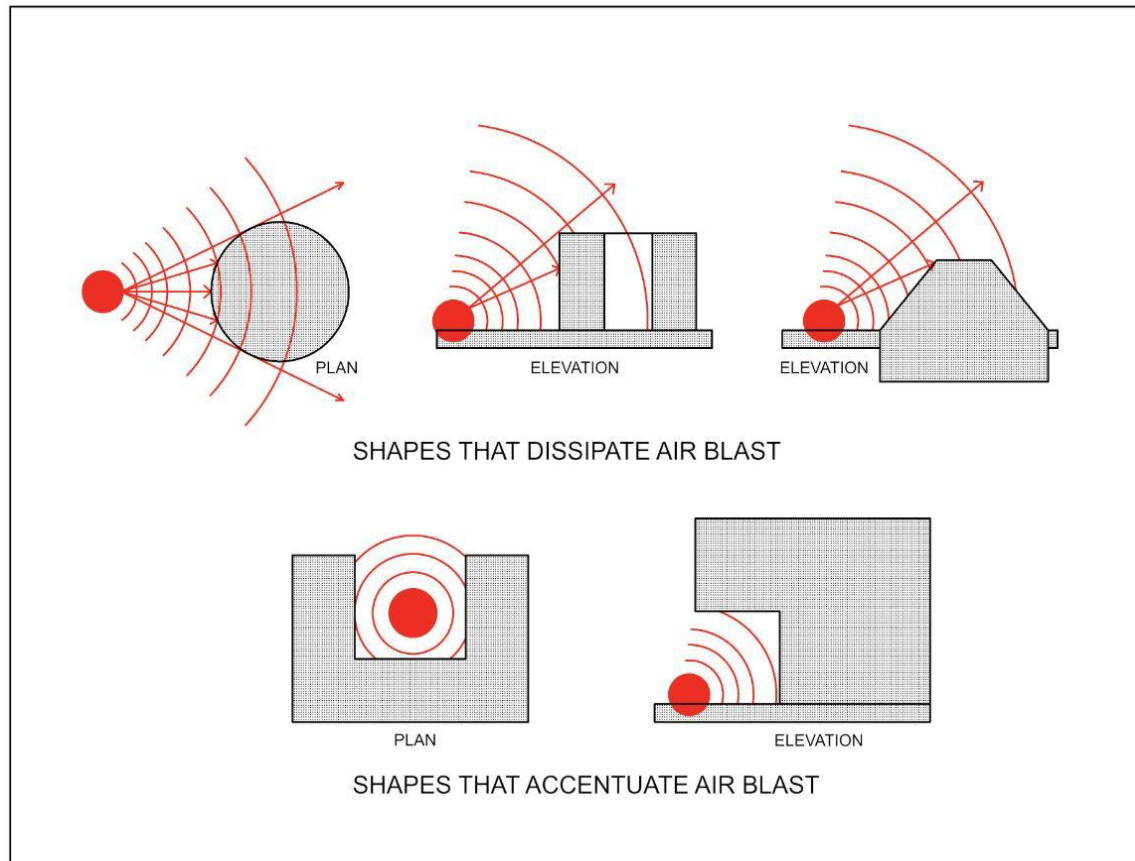
11.2.2 Minimize sharp reentrant corners and overhangs

These features of a building trap the shock wave and amplify the effect of the air blast. Large and gradual reentrant corners have less effect than small and sharp corners (FEMA 2004).

11.2.3 Use circular building shape

The reflected pressure on the surface of a circular building is less intense than a flat building. Convex shapes are preferred over concave shapes (see Figure 27).

Figure 27. Effects of building shape on air blasts.



AFFECT OF BUILDING SHAPE ON AIR BLAST

11.2.4 Use minimal ornamentation

Simple buildings without ornamentation prevent excess debris from flying during an explosion (Hinman 2017). If there is ornamentation, use lightweight materials such as timber or plastic, which are less likely to become lethal projectiles during explosions. Avoid brick, stone, and metal. The following is recommended for buildings:

- Simplify light fixtures and overhead equipment
- Use plastic or fabric curtains instead of metal window-blinds
- Place heavy equipment such as air conditioners near the floor
- Desks, computer monitors, conference tables, and other furniture should be placed away from the windows.

11.2.5 Buried roofs

Bermed walls and buried roof tops are shown to be highly effective for military applications. It is also helpful for energy efficiency. Parking should not be permitted over buildings (Hinman 2017).

11.2.6 Reinforced walls

[Poured in place reinforced concrete](#) will provide the highest level of protection (USACE 2018). Historically, cast-in-place ductile reinforced concrete was used for military bunkers, and has significant mass which improves the response to explosions. However, it must be ductile design. The following is recommended for reinforced walls:

- Precast concrete panels
- Masonry
- Metal stud systems
- Do not use timber

11.2.7 Blast resistant windows

For blast resistant windows it is best to use laminated annealed glass. While strengthened window design may be helpful when exterior forces act against the building (terrorism, hurricane, wind, and earthquake). However, some other factors should be considered,

1. In the case of interior explosions, will the windows increase smoke inhalation injuries by preventing the smoke from ventilating through the windows that normally break in an explosion event?
2. If a fire occurs, will it be more difficult to escape, get access to the injured or vent the building?

Doors should open outward so that they bear against the jamb during the positive pressure phase of air-blast. Door jambs can be filled with concrete to improve their resistance (USACE 2018).

11.2.8 Interior courtyards

This could be a good way to bring in light and a place for a natural atrium for building occupants without making the building more vulnerable to threats.

11.2.9 Building interior layout

Program lobbies, retail, loading docks, and garages to the exterior of the building, while protecting key secured programs such as mechanical and offices. The structuring of spaces in this fashion provides a buffer to protect the most populous or important areas in a building. Secured areas should not be placed above or below unsecured areas. The following designs are also recommended:

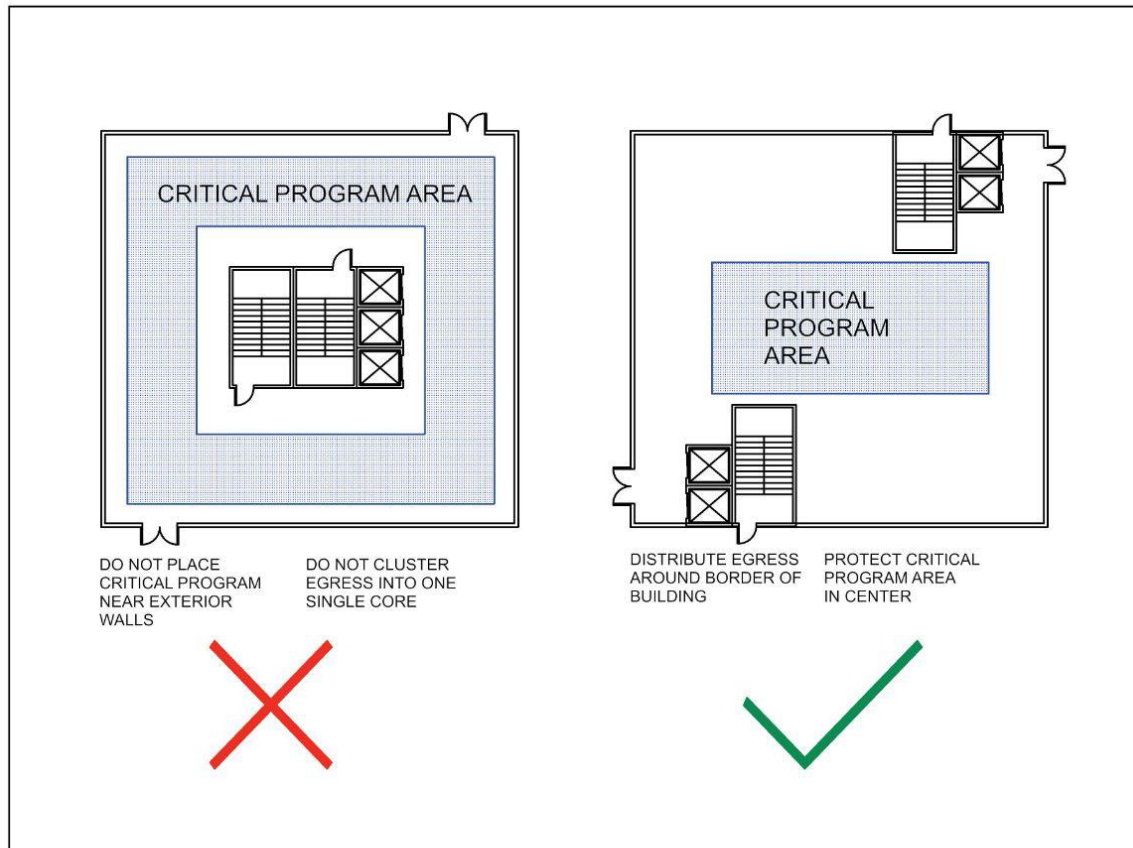
- Emergency function areas should not be placed adjacent to the lobby and should be separated by a buffer area like a corridor or storage
- Exposed structural columns should be minimized inside unsecured areas
- Emergency functions and elevator shafts should be placed away from internal parking areas, loading docks, and other high risk areas.

See Figure 28 for the concept of protecting key secure programs.

11.2.10 Distribute egress routes around building

Do not cluster egress into one single shaft and separate them far as possible to increase the chance of escape. Do not use glass along primary egress paths. The elevation side of emergency exits should be free of overhangs and other ornamentation that may block exits. See Figure 28.

Figure 28. Egress and layout most optimal for antiterrorism.



EGRESS AND LAYOUT

11.3 Precedents

11.3.1 Making bollards aesthetically pleasing

Public furniture, large art installations, and trees all contribute to making a city more livable, but also safer. It is important for antiterrorism elements to blend into infrastructure, as it provides occupants of the buildings more peace of mind and reduces constant anxiety of potential threats.

New York City, New York, for example, integrates bollards into the cityscape by [incorporating art, painting or fitting bollards with plastic coverings](#) (Sweitzer and Clemoes 2019). Alternatively, concrete benches allow pedestrians a place to sit, but also serve the role to protect citizens from vehicle attacks, preventing vehicle access to sidewalks. Large concrete planters could serve as multipurpose systems of adding greenery to a building and protection.

Crash and attack resistant bollards are required for all US military and governmental buildings. However, these bollards can take on any kind of form that occupants can barely recognize they are there for safety. An example of a custom-designed bollard are the [bronze bollards called “No Go”](#), designed for New York City, New York’s Financial District, by Rogers Partners Architects+Urban Designers (Quito 2016). They look like sculptural objects that allow Manhattans to gather and sit around. In army installations, concrete protection devices are often combined with U-shaped bike racks, doubling in function.

11.3.2 Emirates Stadium—London, England

Fortified concrete letters [spelling out ARSENAL](#) serves two purposes (Barry-Jester 2017). This sculpture is located outside the stadium where the soccer team plays in London. It is an iconic place for tourist fan photos, but also serves as a protection device for the building and the occupants inside the stadium during large events.

12 Conclusion

Resiliency in design is a dire need. There are no one-size-fit-all solutions for creating resilient buildings. It is important for the designer to figure out what is best for each unique project, weighing the advantages and challenges of each site, sorting through the available design techniques, and analyzing the programmatic goals specified during the schematic phase.

Designers and engineers must incorporate resilience strategies to maximum extent: it must start at the conception of a project in order to enact radical change. Reflecting upon economic, social, and technical factors, it is advantageous to consider what we can do to design resistant buildings, structures that are built to last, that are protective of people, the environment, and important functions. This is a call to action to take a deeper look at how design decisions can impact the lives of many people in the future.

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Abbreviations

AQI	Air Quality Index
BIM	Building informational modeling
BMC	Bergen Mobile Concrete
BOM	Bureau of Meteorology, Australia
CAL FIRE	California Department of Forestry and Fire Protection
CDP	Carbon Disclosure Project
CERL	Construction Engineering Research Laboratory
CHP	Combined heat and power
CTA	Creative Architects
DA	Department of the Army
DCAT	DoD Climate Assessment Tool
DoD	Department of Defense
DPR	Direct potable reuse
EF	Enhanced Fujita scale
F	Fujita scale
FMS	Fiji Meteorological Service
FRP	Facilities Reduction Program
IAQ	Indoor Air Quality
ICC	International Code Council
ICE	Internal combustion engine
IECC	International Energy Conservation Code
IMD	India Meteorological Department

IPCC	Intergovernmental Panel on Climate Change
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
LEED	Leadership in Energy and Environmental Design
MF	Météo-France office
MOB	Mobile offshore base
NCEI	National Centers for Environmental Information
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
NSSL	NOAA National Severe Storms Laboratory
PCN	Powerhouse Company News
PT	Pressure-treated
PV	Photovoltaic
RDF	Remote delivery facility
T	TORRO scale
TV	Temperature variable
UCANR	University of California Division of Agriculture and Natural Resources
UGBG	Urban Green-Blue Grids
USACE	US Army Corps of Engineers
USCRT	US Climate Resilience Toolkit
USFS	US Forest Service
USGBC	US Green Building Council
VA	Veterans Affairs

VLFS	Very large floating structures
WBDG	Whole Building Design Guide
WTE	Waste to energy

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