

# Simulating gentle failure as an approach to building resiliency

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## Abstract

Current research and policies in resiliency focus on the definition of future risks and conditions but lack guidance on how to deliver a resilient building in practice. This paper describes a “gentle failure” approach to resilience in the context of multiple potential disasters as well as long-term weather change used in the design of an art center/ residence in California. The idea of future proofing buildings is reframed by focusing on adaptability and diversity of strategies rather than oversizing systems to respond to more extreme conditions. Simulations of thermal comfort and varied load scenarios were tailored to the needs of the project. This helped to define resiliency targets, specify envelope assemblies, design mechanical systems, develop a gentle failure implementation plan and sizing energy storage and production systems.

## Key Innovations

- Methodology of implementing resiliency strategies in practice
- Simulation as a tool to explore client decisions and expectations for resiliency, building and systems design
- Description of an iterative analysis process based on simulation results through a range of power failure scenarios
- Simulation used to answer design questions with the goal of gentle failure, not futureproofing building performance by oversizing equipment

## Practical Implications

Simulation practitioners should always work with the client and design team to define priorities and resiliency expectations that can be accommodated within the energy and economic budgets.

Simulation for resiliency should be more nuanced than configuration and analysis of the energy system sizing.

Thermal and luminous autonomy are crucial simulation analyses to develop a staged approach to mechanical and electrical systems.

## Introduction

In California, increased frequency of events such as mudslides and wildfires, as well as the potential for earthquakes, have pushed projects to consider the building’s ability to withstand extended power outages.

Similar strategies may be appropriate for dealing with challenging thermal conditions that will result from climate change (Jentsch et al, 2008). With design efforts to achieve zero energy performance, building teams now extend their analysis to strategies that maximize passive survivability for an indefinite period of time, responding to the increasing demand of people who live in the fragility of the California landscape. An important method of resilient design focuses on comfort and lack of reliance on machinery. This method goes beyond the installation of equipment to maintain critical life-support conditions in the event of extended loss of power, fuel or water, strategies often used in essential services resilient design.

This paper builds on previous research for essential services buildings and describes the process to develop a nuanced approach to resilience – what we call “gentle failure”, with a detailed discussion of how to implement this method in practice through iterative simulation and design. This gentle failure approach contrasts with the concepts of “engineering resilience”, stability and robustness typically considered within building resilience literature (Rajkovich et al, 2019), and instead borrows from concepts found in “ecological resilience”: adaptation to change and uncertainty, and the need for transformation in current practices mainly through passive design approaches.

## Context

Projects addressing natural disasters and climate change do so by fusing resilience and sustainability strategies into a more comprehensive approach to adaptation. Every year the environment shows that resilience is increasingly critical for every stage of design. Policies are being developed to address this issue but there are still not many examples of how this research applies to and is integrated into practice (Rajkovich et al, 2019). Literature on resiliency typically addresses urban-level planning but not how simulation supports the design process nor the methodology of implementing potential strategies in practice (Trojal et al, 2018).

Similarly, publications about how to obtain data representing climate change scenarios to be used in building simulations (Dickinson et al, 2016) are available but do not describe how to think through a range of possibilities. There is little guidance on how to use modelling results to design both the building and the systems as a strategy that responds over time.

Certification systems such as the RELI 2.0 provide guidelines for resilient design and construction but do not cover indefinite building operation following a catastrophe beyond the first 96 hours. The guidelines do not address simulation or performance analysis, nor specific quantifiable performance metrics and criteria. As in LEED, credits can be cherry-picked to obtain a minimum number of points and obtain a certain certification level but projects are not required to rely on a more sophisticated analysis. We have found this necessary to design a building that interacts with the exterior environment to generate resiliency; one that opens to daylight and natural ventilation, brings the indoors and outdoors into close relationship, and still provides physical and psychological refuge from extreme outdoor conditions.

### **Gentle Failure vs Catastrophic Failure**

While failure is still not commonly discussed during the design process of a building, the failure mode (understanding what happens when a system fails) is useful to predict how a building will respond to a power outage event. Even more it explains how well a space is in tune with its environment. For example, a hermetically sealed building will need to be evacuated soon after a power failure. The building will likely overheat, may be too dark to move around once the battery-powered emergency lighting fails, or may run out of breathable air. In contrast, a daylighted and passively ventilated building will allow for a longer useful occupancy, if not an indefinite period of habitation. A building designed to function during emergencies can also better take care of itself and its occupants during non-event times which form the majority of the life of the building.

### **The Gimli Glider Emergency**

A famous example of gentle failure is the case of the “Gimli Glider” Emergency (Nelson, 1997). On July 23, 1983, a domestic passenger flight between Montreal and Edmonton (Canada) ran out of fuel midway through the flight. A series of strategies allowed the pilots to adapt the Boeing 767 plane to “passively” fly (glide) to an emergency landing in Gimli, Manitoba.

Various redundant systems allowed the pilots to respond to the lack of fuel. The Ram Air Turbine (RAT), a propeller driven hydraulic pump supplied just enough pressure to move the control surfaces and enable a dead-stick landing. The wings design made gliding possible once the plane dropped into the airstream. The landing gear had a “gravity drop” option to fall and lock in place. The pilots’ passive operation included slowing the plane when it approached the runway too high and too fast, while lacking dive brakes, the way a sailplane pilot would do: crossing the controls and throwing the 767 into a vicious sideslip, then managing to wrestle the plane back to a straight and level approach just forty feet above the ground.

Redundancy, adaptability and “gentle failure” were exhibited in this unique aviation incident and could be similarly used as the goals to design and operate buildings capable of “gliding” through power outage events.

## **Simulation and analysis for resiliency in practice**

### **Essential services buildings**

This paper builds on questions of resilience studied in essential services buildings, and modeling strategies developed for design teams to meet zero-net energy (ZNE) goals (Santiago Trojaola, I. et al., 2017). Simulation in these cases focused primarily on sizing energy systems for 72-hour power outages through both strategic staging, renewable energy production and battery storage.

Strategic planning for a regional hospital expansion revealed the complexities of including the issue of resiliency in the building design process. The hospital analysis used high level analytics to identify patterns and factors in energy use in the existing campus in order to determine and quantify the energy needs in case of an emergency. This informed the strategies developed for retrofit and redesign and helped to identify the opportunities with greatest potential impact on passive survivability performance. The analysis addressed resiliency defined through an engineering perspective of reducing building energy use and maximizing capacities of energy storage and generation systems.

Methods applied in a second project, the design of a new Police Station, aimed for the project to be self-sustaining during an emergency. Our simulations included thermal autonomy analysis, comfort load factor and sensitivity analysis and predictive energy performance during 72-hr periods representing extreme event scenarios. The use of thermal autonomy as a design approach underlined the deficiencies of standard industry practice in evaluating building performance for passive survivability.

In both projects, we identified the range of critical functions in essential services buildings and underlined the stakeholders’ varying priorities. The process raised divergent views on how to address adaptation and all measures faced scrutiny based on budget considerations. Stakeholders had to consider a wide range of issues (budget, occupant behaviour, facility management and maintenance) and keep project priorities consistent with expectations of large essential services building projects.

### **The art center / residence**

These methods were applied in the design and analysis process of an art-center / residence in California with construction for the building scheduled to finish by November 1st, 2021. The process recognized future environmental challenges and extended performance goals to address potential disasters and climate change scenarios. Focus on resilience was defined as the building’s ability to adapt to, and/or rapidly recover from heatwaves and hazardous air quality conditions without access to utility grid power.

The two-story, approx. 3,000 sqm (30,000 sqft) project consists of a mixed-use program combining an art center (artist studios, exhibition galleries, office spaces and a 30-people theater) with a single-family residence. Occupancy will vary from two permanent residents to a number of

artists in residence, to fundraising and exhibit events hosting up to 220 people.



Figure 1: Project Rendering by Architect.

The building (shown in Figure 1) sits at the top of a ridgeline with expansive views south to the Pacific Ocean from the top floor. The shape was designed by the architects and clients as an art piece to maximize these views without creating a visual disturbances. The project is conceived as an extension of the ridge top, with the entirety of the program underneath a continuous green roof garden and within a building shell and structure of high-density concrete. The curved roof is sheared off in areas to open up walls to views for large entertainment and gallery spaces, as well as creating smaller working spaces and intimate living areas for the residential program. The lower level is half buried in the ground and daylit through courtyards.

Programmatic and site conditions constrained the design, while the budget was primarily determined by value for cost. The clients desired an environmentally resilient Net-Zero building with superior occupant comfort and efficient energy systems. They wanted the ability to maintain operation during a power outage in response to environmental events and to function smoothly as climate change continued to impact the weather.

### Initial Studies: Predictive Energy Performance

Initially, both the design team and the clients were interested in analyzing energy performance from a Zero Net Energy standpoint. The first studies were developed to predict the building energy use under normal operation and typical annual weather conditions, then compare the modeling results to the annual site solar energy generation potential.

The Energy Plus model contains envelope geometry, shading devices (exterior automated shades and overhangs), and orientation, as well as assumptions about ventilation, construction assemblies, and internal gains. Typical meteorological year (TMY3) weather data were used for the analysis.

Given the fact that a significant portion of the building envelope is buried in the terrain, careful consideration was given to the ground temperature conditions. These were calculated using the ground heat transfer preprocessor in EnergyPlus on exterior side of retaining basement walls and slab.

By carefully subdividing the building into 42 thermal zones based on different perimeter exposures, internal loads and schedules, we obtained a first set of results assuming mechanical conditioning with “Ideal Loads Air Systems” in EnergyPlus. We defined a “High Load Suite” and a “Low Load Suite” based on the range of assumptions of internal load densities (lighting 4-8W/sqm, receptacles 6-12W/sqm), cooling thermostat

setpoints (22-26C) and usage profiles (frequency of large occupancy events) to estimate building energy use (Table 1).

Table 1: Predictive Energy Use results (GJ/yr).

Energy End Use	High Load Suite	Low load Suite
Space Heating	2	3
Water Heating	64	64
Space cooling	167	39
Lighting	122	88
Equipment	276	138
Other (EV, Pool)	223	223
Project Total	854	556

Using a site model and actual massing, we created diagrams identifying possible areas to install PV on site plan. Reviewing annual solar access results, we modeled a series of photovoltaic panels distributed around the southern side of the project and tilted to match the existing slope. Since the surface upon which the panels will be mounted is curved, we assumed that the panels selected won't be able to cover the whole surface completely, and that panels with an output of 205W/sqm and 20% efficiency would be used. We compared solar energy produced annually for a range of tilt angles, from horizontal (flat) to vertical to determine the ideal angle for that slope. This analysis served as a baseline estimate (Table 2) and showed that a total PV area of 352 sqm on that slope generated 236GJ/yr (37% to 71% of the building-only energy use depending on the load suite).

A net zero analysis to estimate additional PV area using flat horizontal panels needed to produce as much energy as the project uses showed that 120 sqm of PV panels with the same specifications would be required to generate electricity for the building energy use only (no EV charging, no pool equipment).

Table 2: Building Energy Use and Generation Intensity (GJ/sqm).

	Energy Use Intensity	PV Energy Generated by Building Area
High Load Suite	0.36	0.09
Low Load Suite	0.23	

These studies were used to review load assumptions (occupancy, schedules, equipment and lighting load densities, etc.) with the clients and to discuss how the estimate for energy use could vary based on factors such as occupant behaviour and building operation.

### Simulation and analysis for gentle failure

In the art center/ residence, we approached building performance analysis and simulation differently. Rather than using the commonly accepted benchmark of 72hour (3-day) periods, the adaptation of building performance and operation by its occupants for an indefinite power outage was the focus of the analysis. The project embraces the gentle failure of the building and highlights the capacity of systems to reorganize, applying strategies inspired in the ecological resilience domain (Rajkovich et al, 2019).

Simulation for gentle failure follows a different analysis sequence. Focusing on the occupants first, sophisticated

tools are used to answer more nuanced, complex questions starting in the early design stage. Our process addresses adaptation, diversity, staged response to failure and redundancy.

In this process, simulations of annual thermal and luminous autonomy become crucial. Thermal comfort load factors help define the envelope design and material specification. We used Energy Plus for both energy and thermal comfort simulations, and Radiance to analyze available levels of daylight, assist with shading control and curatorial levels for art conservation but also to quantify the cumulative effect of solar radiation in spaces with overheating concerns due to large south or west facing curtain wall areas.

The results set the basis for simulations of staged responses of mechanical and electric lighting design systems. Specific questions on the design and sizing of energy storage and generation systems were the final part of the analysis process.

The occupant-centered analysis used during early design phase relied on iterative simulations and analysis to switch the project's focus from achieving resiliency to collaboratively developing an approach of gentle failure that explored the project's goals beyond an energy use target. This contrasts with a segmented approach in which energy use strategies are considered separately and resiliency is reduced to energy generation and storage system sizes.

### Simulating failure and adaptation

A series of mudflows occurred in Southern California in early January 2018 during the building design process. The disaster occurred one month after several major wildfires in the same area. These events increased the clients' concerns about extended power outage scenarios beyond occasional utility grid unreliability and annual Net Zero Energy goals, and provoked a deep analysis of failure scenarios. The analysis switched focus to occupant thermal comfort in order to assist the clients to define their expectations during an extended power outage that could last beyond 72 hours.

Thermal comfort autonomy studies looked at how many hours the building would be uncomfortably warm or cool throughout a typical year if the mechanical systems were unavailable. These simulations were calculated revising the Energy Plus models used for the predictive energy use analysis, adjusting the inputs for internal loads and removing the preliminary mechanical systems. Results were compiled and post-processed using custom scripts applying thermal autonomy analysis methods as described by Levitt et al (2013).

We analyzed when people would be uncomfortable, how uncomfortable they would be and for how long in each thermal zone using the ASHRAE Standard 55 - adaptive comfort model. Heatmaps show the hours over the year that the operative temperatures are out of the comfort range in each space (Figure 2). Based on periods of discomfort, we identified four different space types.

1- Spaces with no overheating hours, where no cooling is needed.

2- Spaces with overheating and cold discomfort periods. By observing when each discomfort happens compared to the predicted occupancy of the space, we reviewed the need to introduce strategies to mitigate the discomfort. For example, cold discomfort happens during the night, but also when occupants are likely not present in the gallery and art exhibition spaces.

3- Spaces with high internal loads, where overheating is mostly caused by the heat released by the equipment, and where the actual use and operation of the building will ultimately determine the thermal comfort conditions.

4- Spaces with overheating due to solar heat transmitted through the south/ west facing windows (providing views to the Pacific Ocean).

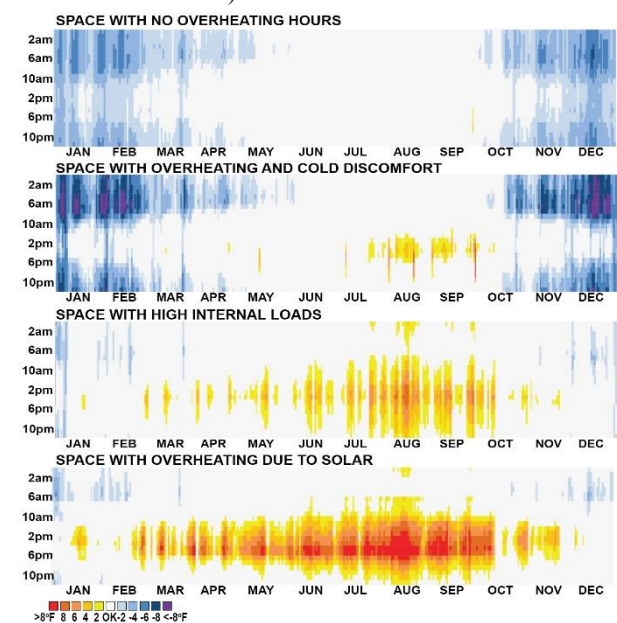


Figure 2: Degrees from comfort in the four different space categories.

Diversity of interior conditions based on this thermal comfort space categorization introduced the idea of climate migration (Mayer, 2016) within the building, adapting and redistributing the building program and occupancy as needed to the thermally and visually comfortable spaces during a power outage.

### Simulation for diversity

To identify the factors associated with decreased comfort and to compile a set of specific priorities for improvement in the current design, the analysis included a load factors sensitivity analysis using a method described by Brown et al (2014). These studies explained to the clients the factors affecting thermal comfort and assisted the design team with the envelope design and specifications.

Reviewing the load factors sensitivity analysis for each space category, the team discussed how the factors associated with increased thermal discomfort in the analysis were the solar radiation through the windows and the heat released by the equipment.

Results also showed that the building structure made of concrete was effectively acting as a thermal battery; absorbing the excess heat when there is too much heat gain and releasing it when the outside conditions cool down, extending periods of thermal comfort that do not require mechanical conditioning. Thermal mass and ventilation were prioritized to increase comfort in spaces with periods of overheating and solar heat gain through windows was identified as needing further analysis.

Ensuring the design provided an adequate amount of thermally and visually autonomous spaces with no mechanical nor electric lighting systems became the focus of the analysis efforts at this point of the design process. This required a multi-level design approach to balance shading, daylighting and thermal needs and diversify the strategies to effectively respond to the interior conditions depending on the time of day, season and program requirements.

Radiance simulations with building geometry obtained from a Rhino model were used to visualize cumulative solar radiation on the floor for the whole year (Figure 3) and daily patterns of peak instantaneous solar loads in each space for the 21<sup>st</sup> of each month.

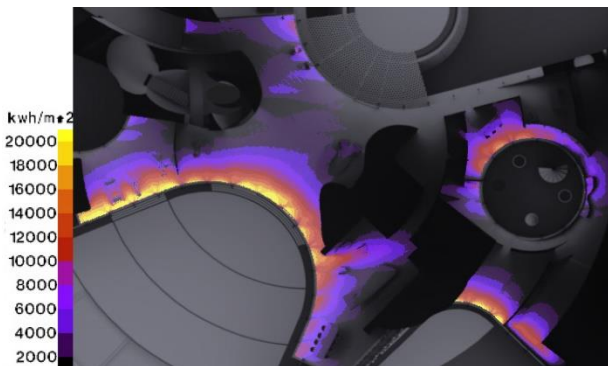


Figure 3: Cumulative annual solar loads on main level.

Simulation analysis also supported the goal of extending the periods of thermal autonomy by using multiple iterations of the EnergyPlus model, and testing a series of design alternatives. The goal was to understand building performance with variations of insulation in the roof and wall assemblies, thermal mass and glazing specifications. In order to predict the ideal insulation specifications for this climate and this site, we parametrically modified the thickness of the insulation in each part of the envelope to identify the value on the roof and in the walls that would optimize the building performance with reasonable construction and cost implications. We compared the heating and cooling loads in each case graphically, observing how both curves reach a sweet spot- the point of diminishing returns where adding more insulation has minimal impact.

These results were compared to the daylighting and curatorial requirements and used to define the specifications for the envelope.

### Simulation of staged response

The thermal autonomy studies also addressed performance under possible scenarios by using detailed, multivariable performance data over periods representing

historic extreme weather events (heatwaves). After reviewing EPW files generated with methods described by Dickinson et al, 2016 to represent various emission and global warming scenarios, we decided to connect to the clients' personal experience by using available weather data from Actual Meteorological Year (AMY) files from the same location, and selecting a one-week period in 2016. Both daytime and night-time temperatures were higher than average for five consecutive days in September and the highest and lowest monthly average temperatures were hotter than in the TMY3 data. Results showed that periods of thermal discomfort were more frequent and more extreme in the art center spaces. Especially impacted were short periods of large occupancy during exhibit openings or fundraising events. These were beyond what the passive strategies could handle under extreme weather scenarios.

In order to include a staged response to conditioning the interior spaces, redundancy and diversity of means were provided to address varying needs. When outdoor conditions allow, natural ventilation through large hangar doors in the main exhibit spaces will provide increased air circulation. Operable skylights, windows and sliding doors also contribute to optimizing the airflow through stack effect and cross ventilation.

When the outdoor temperature is too high or the air quality is too poor or unhealthy (such as during wildfire events), mechanical systems would be needed to condition the building and filter the outside air.

We added an air-based system in the Energy Plus model to assist with system sizing and understand occupant thermal comfort when the building is mechanically conditioned.

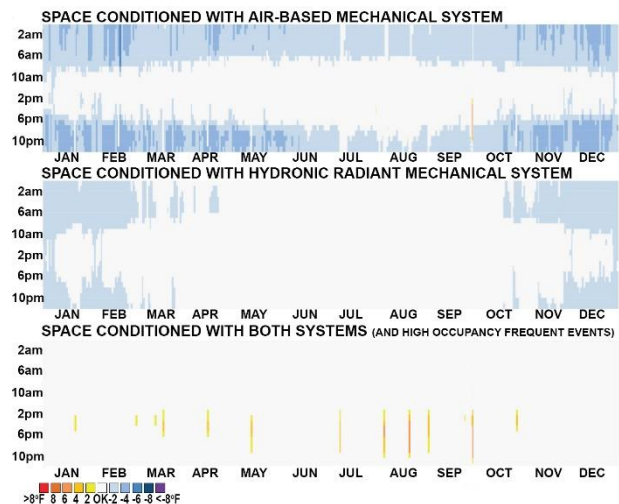


Figure 4: Degrees from comfort using air-system (top), hydronic radiant system (middle) and a combination of both (bottom).

By reviewing thermal comfort conditions with this system, we noticed that it would effectively eliminate the overheating periods in all space types, but also that all spaces consistently feel too cold. An air system could cause local discomfort if the surface temperatures are cold, even if the air is hot. The team compared these

results to those from a model with hydronic radiant systems, warming up the floor and thus affecting not only the air but also the Mean Radiant Temperature (Figure 4).

### Designing for redundancy: futureproofing the conditioning systems without oversizing

As a result of these discussions, the team started to outline the implementation of a gentle failure approach to building conditioning and occupant comfort to make a staged response possible depending on the timing and duration of a power outage. This response relies on two parallel systems: a hydronic radiant system embedded in the concrete topping slab and a supplemental air-side system with Fan Coil units.

The radiant system will be the default conditioning system if interior conditions fall out of the comfort range during normal operation.

During an extended power outage such as one caused by a natural disaster, the radiant system will only provide heating in the evening and early in the morning. If the average temperature of the concrete floors drops below a minimum setpoint, valves will bring hot water at a fixed supply temperature to warm up the floor and slab surfaces. During the day and for the main level only, if solar radiation causes the floor temperature along the perimeter to overheat, pumps circulate water continuously to distribute these localized radiant loads throughout the floor mass. This offers a low-energy using approach to address the overheating periods noted in the thermal autonomy studies by tackling the surface temperatures affecting occupant comfort instead of relying on the air-based systems.

Radiant systems on the main level are also designed to accommodate future 3-way valves on both supply and return pipes to allow switching individual zones to cooling mode when the average temperature of the floor sensors rises above the applicable setpoint.

The air system would only be used occasionally. It is designed to accommodate deviations in internal loads that may cause occupant discomfort when a quick response is needed due to changes in occupancy (such as fundraising events or art exhibition openings), but also to address periods of unhealthy air quality, such as wildfires. Parametric analysis of the impact of various cooling thermostat setpoints showed the potential energy use reduction of adjusting these if the air system is needed during a short (up to 4 hours) power outage event.

### Modeling Energy Budgets: re-defining client expectations for gentle failure

To provide redundancy and diversity during power outages, the project includes an energy generation system consisting of a photovoltaic array and a diesel generator for overcast periods or battery replenishment needs, and an energy storage battery system. In addition to installing these systems, the building was designed for adaptability and gentle failure based on progressive resiliency stages. At this point of the design, discussions with the clients addressed duration of each resiliency stage, identifying critical spaces and required loads (what equipment was

needed in what space and for how long). The clients' expectations established the basis of design for the energy generation and storage systems (battery + PV) as:

- Allow normal building operation for up to 6 hours with no large events.
- Allow reduced operation for a minimum of 24 hours without solar energy.
- Allow reduced operation for up to 3 days (72 hours) with solar energy generation.
- Allow minimal operation indefinitely with solar energy generation.

An estimate of energy budgets based on these requirements was developed in spreadsheet form. This space-by-space analysis included the loads and usage profiles for HVAC, lighting and receptacles during each of the stages. Results were used to set the targets for resiliency stages and assist with load sizing calculations and specifications of the energy storage (battery) and energy generation (PV arrays) systems.

The building is designed to allow for the following three resiliency stages to be implemented:

1. STAGE 1- Normal Operation: regular occupancy, when all systems (HVAC, lighting, equipment, pool and EV charging stations) are available, with an estimated maximum energy use of 1200 kWh/ day.
2. STAGE 2- reduced operation: to be implemented during a short power outage. Load reduction strategies for this stage were estimated to reduce energy use to a maximum of 380 kWh/ day.
3. STAGE 3- minimal operation: to be implemented during a long power outage or during cloudy days (unavailable solar energy), with a maximum energy budget of 150 kWh/ day.

A resiliency control system is included in the project allowing the occupants to transition across these stages automatically (Figure 5) based on the needs to balance energy sources, battery level with power consumption and effectively reduce energy use as needed during outages.

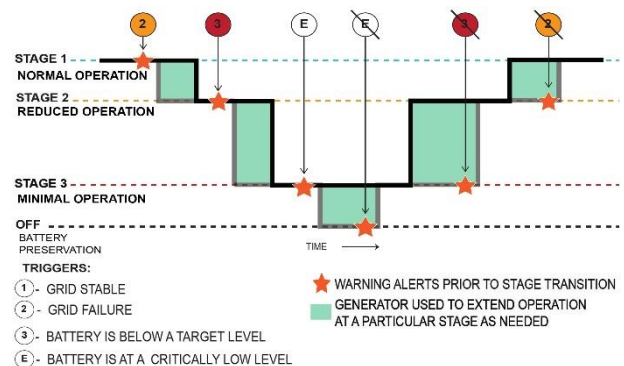


Figure 5: Implementation of Resiliency Stages

### Sizing energy generation and storage systems

To study battery sizing needs with respect to the clients' expectations, we compared the daily energy use estimates obtained in the energy budget analysis and the desired duration for each stage as discussed with the owners. We looked at how long the building could operate after being disconnected from the grid, relying on battery storage and

PV panels as sources of energy for any 72-hr period throughout the year, both under Stage 1 (Figure 6) and Stage 2 operation.

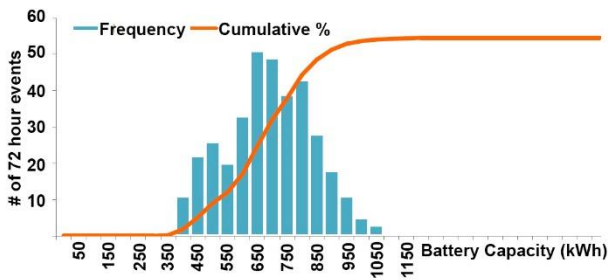


Figure 6: Battery capacity requirements for 72-hr event under normal operation and solar energy generation

When planning for extreme events, variability of solar radiation must be taken into account to ensure that the building is prepared to sustain operations during cloudy winter weather. In our analysis we used a 72hr running average to estimate the battery size and studied the cloudiest period (Figure 7) (mid-October) in the weather data. Even if we understand that these conditions are not frequent in this region, it is also an example of a Pacific Storm event, when power outages are indeed most likely to occur. We assumed for this study that the building will not be using the battery on a regular basis, in other words, that the battery is full at the beginning of the power outage.

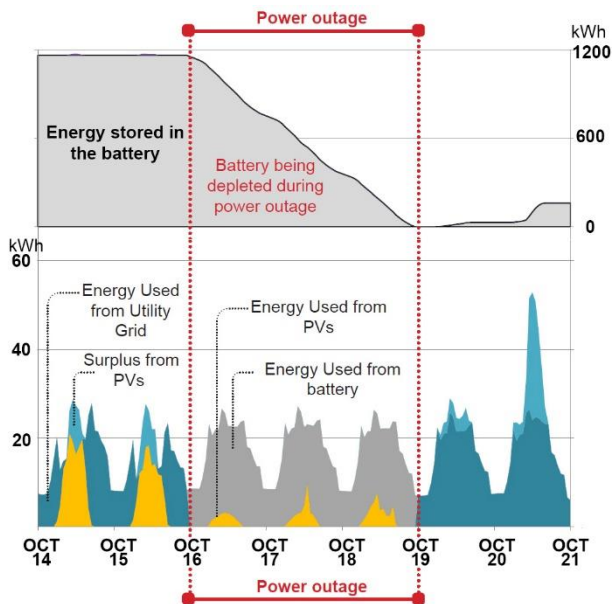


Figure 7: Energy use and battery energy storage for cloudiest 7 day period with a 1200kwh battery

After reviewing the simulation assumptions and the histograms obtained through the analysis, the team decided to approach energy storage sizing in a gradual manner: start with a modestly sized system and monitor the building energy use and solar power generation.

A 300kWh battery will be installed and allow for potential future expansion. When sizing a battery, an accurate estimation of expected energy loads is paired with the pattern of energy generation. The battery size needs to be

large enough to bridge the gaps between the two. Given that the preferred method of energy generation is solar, one also must assume that a power outage may occur during a storm delivering with reduced production due to cloudy skies. Still if one adds up the loads and makes simple assumptions on energy use, the battery may end up oversized. An oversized battery has disadvantages, other than the obvious, cost and needed storage space, such as potential longevity issues as the batteries may not be optimally used.

Modeling results showed that the photovoltaic array should be able to produce an average between 193kWh and 232 kWh per day in order to be a contributing element to the resiliency of the project.

#### Adaptability: Performance monitoring system

Actual performance during occupancy will be monitored with a comprehensive performance monitoring system consisting of sensors to monitor indoor environmental conditions, electricity production and usage, and weather conditions. This will provide the clients with access to data in real time, trends and usage profiles, allowing them to make informed decisions and adapt their behaviour.

The design and simulation team will review monitored energy use data within 12 to 24 months post-occupancy to identify whether additional battery capacity or solar production is needed. If the power production is too low and solar energy will not be sufficient to maintain the energy use., the diesel generator will become the primary source of energy. Other than the use of fossil fuels the disadvantage of this is that the generator can be less reliable than solar and there is a limited amount of diesel fuel on site. In case of a long outage, it is possible that the fuel will be exhausted particularly if the generator is required for most loads.

The monitoring data will also be used to establish ongoing comfort and energy performance for use in future performance diagnosis and verification, track energy production versus use of the building, and track battery charging and discharging.

#### Conclusion

In most resilient design, passive survivability is achieved by including appropriately sized energy production and storage systems to handle a few days of outage. The gentle failure approach develops an implementation plan to allow the building to “sail itself” through power outages, much as a sailboat with a small auxiliary engine for periods of no wind and emergencies. When a system sizing approach to simulating resiliency was not able to address the range of failure scenarios in the site location, a creative way of thinking explored the clients’ priorities, redefined their expectations and drove consensus throughout the design process quantitatively comparing how these expectations affect the design.

Gentle failure was the key concept driving the simulation process quantifying and informing aspects of a resilient design that would have been approached otherwise from rule-of-thumb or design guideline perspectives:



- DIVERSITY of conditions and strategies available: thermal autonomy simulations identified a range of space categories to support the idea of migration in climate design at the building scale, with special granularity given to the time of the day and the seasons. Comfort load factor analysis informed the design and specification of various high performance envelope features.

- SLOW PACE or STAGED RESPONSE: comparison of annual occupant comfort simulation results for different mechanical system options beyond a single energy use metric, allowed the team to implement an additive approach to conditioning using two systems and futureproofing the building against climate change risks, rather than oversizing equipment.

- REDUNDANCY: space-by space calculations with specific load and usage profiles based on occupant's preferences were used to develop energy budgets for three resiliency stages (normal, reduced and minimal operation). Review of battery sizing requirements for different timeframes and weather conditions supported the idea of combining the PV array with a diesel generator for overcast or low air quality (wildfires) periods.

- ADAPTABILITY: the systems are designed to allow for future expansion. Monitored data will be used to review modeling inputs and revise analysis results based on actual building performance and weather conditions.

Energy performance, thermal comfort, ventilation and daylight are complex to achieve and integral to the architectue. They cannot be "added on" later in the design or post-occupancy even at extra cost. Including these strategies at the early stages of the design produces a building that is sustainable throughout its lifetime, not only during power outages.

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Greg Griffin and his team at Shubin Donaldson Architects demonstrated how innovative buildings can push the limits of the industry's performance goals while still being recognized by their impressive architectural design.

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