Simulation in Support of Zero Net Energy and Resilient Design

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ABSTRACT

As the building industry has moved toward practices that mitigate climate impact and anticipate climate change, there has been a growing interest in related design processes and technologies to protect against environmental risk. Examples of how to develop strategies to meet zero-net energy (ZNE) goals or the questions of resilience in existing buildings have been studied. This paper describes how a critical infrastructure building (a major urban Police Station) holistically approached zero net energy performance and passive survivability in the same design process. Methods applied include thermal autonomy analysis, comfort load factor and sensitivity analysis and predictive energy performance both throughout the year and during 72-hr periods representing extreme event scenarios.

INTRODUCTION

Both zero net energy and resilience aspects of building design are important in order to reduce negative impacts on climate (mitigation) as well as prepare for extreme events resulting from climate change (adaptation). Climate change must be addressed comprehensively through fusing resilience and sustainability strategies into a more comprehensive strategy of adaptation (Achour & Price, 2010). Pasive survivability refers to a building's ability to maintain critical life-support conditions in the event of extended loss of power or water. This is likely to become a standard in the design criteria for certain building types, especially essential services buildings.Passive survivability presents more challenging constraints than ZNE performance, as buildings have to be designed for a 3-5 day period without utilities during any season.

Essential Services Buildings

As part of previous research, strategic planning for a regional hospital expansion revealed the complexities of including these issues in the building design process. The main goals of that project were to reduce energy use and energy cost; to provide energy and water reliability in extreme events; and to increase sustainability. The design team had to solve the task of expanding an existing facility without increasing the demand on the grid and by preventing failures in case of an emergency.

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. Initial research included gathering information on existing energy use, energy costs and pulling data from the Building Management System (BMS) system, installing temporary sensors to monitor environmental conditions and electrical loads by use category, and interviews with stakeholders.

Through this, we developed a characterization of energy use patterns and existing architectural and HVAC factors in the existing campus. This informed the strategies we developed for retrofit and redesign and helped to identify the opportunities with greatest potential impact on both net-zero and passive survivability performance.

In the hospital project we developed a methodology to address these two issues holistically, which was then applied in the subsequent police station analysis that is described in this paper. The hospital project identified the range of critical functions in an essential services building and underlined the stakeholders' varying priorities. The process raised divergent views on how to address mitigation and adaptation and all measures faced scrutiny based on budget considerations. These practicalities provided context for our work on the police station.

The hospital analysis also provided specific examples of normal operation and emergency operation requirements for a critical infrastructure project with several scenarios of survivability requirements, for example electrical outage compared to gas outage, etc. This work helped us to look critically at the modeling assumptions and parameters when modeling the police station.

The experience with the hospital project also helped guide our approach in supporting the police station design team who were designing to a ZNE building that would also be self-sustaining in an emergency.

Police Station

The facility under design is meant to serve as a model for low-energy public facilities. In addition, during an emergency that may compromise all utilities, the building should continue operating as usual, with minimal need to be concerned about maintenance of emergency systems. In such an emergency, police officers should be able to focus their full attention on

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service to the public, without concern about refueling generators or selecting systems to take off-line.

These project goals of zero net energy (ZNE) design and passive survivability required a multifaceted approach to analyze design alternatives and to assess performance relative to these goals. Simulation was a critical tool in this study. Below, we present the background research, design alternatives analysis, and performance analyses that resulted from this simultaneous consideration of ZNE and passive survivability.

SIMULATION

Modeling Approach and Assumptions

For many ZNE projects, modeling focuses on predicting the energy use of a design and estimating the amount of renewable energy to be produced on site over the course of a year to equal the energy used by the building. This approach has several drawbacks that limit the performance potential of a project. Performing the ZNE analysis late in the design process prevents the ZNE concept from shaping important design decisions and may affect the project's budget and schedule late in the process. The building performance usually relies on selecting the active systems that would use the least amount of energy to condition a specific design in the given climate, without questioning or quantifying the need for such system in the first place.

In this case, the analysis for the Police Station began with comfort and energy modeling in order to evaluate the potential for the precinct to be net-zero energy on an annual basis and to operate independent of the grid for limited timeframes.

Building simulations used EnergyPlus, a subhourly heat and mass balance simulation engine. EnergyPlus provided a few key advantages for this study, including explicit heat transfer reporting, allowing comparison between variables at every timestep, accurate representation of thermal mass effects and the ability to explicitly control model geometry through Open Studio for Google SketchUp.

Unlike simplified regulatory models, EnergyPlus allowed modeling of the full breadth of approaches we expected to include in pursuit of ZNE performance and passive survivability. For instance, we knew that trees, automated shading, thermal mass and natural ventilation among other considerations could play an important role in determining the performance of the building.

In order to have confidence in predictions of actual performance, we realized that typical ASHRAE schedules of building occupancy could not be used to design for net zero performance, or prepare for passive surivability. Instead, detailed information from the designer and the client was gathered in order to define the zones according to thermal, energy and occupancy conditions. This included some special operational needs typical of police stations, including 24/7 operation with three distinct shifts, holding cells, data and communication centers, locker rooms and a firing range.

Using drawings, envelope characteristics, internal loads, and schedules of the proposed design, the EnergyPlus thermal model was constructed. It was configured to output heat flux for major envelope and internal load characteristics studied in the analysis: infiltration, ventilation, conduction through opaque surfaces (wall, floor and ceiling) and windows, transmitted solar gain, lighting power, and equipment power.

This model was built to analyze the performance over the course of a typical year and identified when occupants would be uncomfortably warm or cold if there were no mechanical system, how uncomfortable they would be and for how long. We used this comfort model for three analytical methods: thermal autonomy study, comfort load factor analysis, and a parametric analysis of improvement measures.

Climate Analysis

The project is located in a mild wet climate, with no extreme diurnal variations in temperature and an overcast sky condition typical with humid weather. Outdoor conditions vary throuhgout the year from a lower limit of 60.1F to an upper limit of 79.2F. They are usually below the comfort range from October through April. Occasional days during the summer (mostly July and August) are too hot with temperatures in the high 80's or low 90's.

The annual average cloud cover is 68% with July, August and September being the only months with an average cloud cover lower than 60%. Normal average yearly precipitation is 37 inches, with the heaviest rain periods between January and May and between October and December. Prevailing winds come from the south-southwest all year round.

Comfort and Thermal Autonomy

First we applied Thermal Autonomy analysis methods as described by Levitt et al (2013) for eight different zones covering differences in orientation, floor, program (different schedules and/or internal loads). This approach of studying the building's passive performance was not only relevant to understand potential for passive survivability; it was also critical to understand how to minimize the use of mechanical conditioning to make the goal of ZNE more easily achieved.

We calculated comfort based on operative temperature. The range of operative temperatures that are considered comfortable is produced by the comfort model used: either the Comfort Model for Conditioned Spaces or the Adaptive Comfort Model (defined by ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy) based on the previous 30 days of outdoor temperature. The Adaptive Comfort Model (defined by ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy), assumes that occupants have access to operable openings, they have a relative sedentary metabolism, and they can freely select what clothing they wear.

The goals of these studies were twofold. First, as the energy use of the building decreases, it becomes easier to achieve zero net energy performance. The study reveals how often a mechanical system would be needed to condition the interior and strategies to adjust the design to minimize the need for such system and HVAC energy use during normal operation. Second, stripping a building of its mechanical systems, replicates the situation in case of an emergency and therefore prepares it to maximize passive survivability. In case of an emergency, the building is therefore designed to perform in what we term "gentle failure" mode. If all utility energy sources are shut down, interior conditions in the building would become uncomfortable slowly, which allows occupants to stay in the building and keep normal operation for some time, even if energy is not available. In a building designed using traditional methods that do not consider passive survivability as a prime performance goal in the design process, interior conditions rapidly deteriorate and the building would becomes uninhabitable quickly, which is a critical problem for essential services buildings.

For normal building operation, this analysis used the ASHRAE Handbook of Fundamentals Comfort Model, 2005, and assumed that operative temperatures between 68F and 74F for the occupants to feel comfortable. This narrow range is due to the fact that police officers are required to wear full uniforms and the designed mechanical systems in all spaces are radiant floors and Dedicated Outside Air System (DOAS).

During emergency periods, it would be possible to completely shut down the radiant system and provide only mechanical ventilation with unconditioned air. If occupants were also given the chance to adjust their clothing to thermal conditions and open or adjust operable openings to the outdoors, the ASHRAE 55- Adaptive Comfort Standard could be applied. This Standard establishes that the temperature range for comfort would vary across the year between a lower limit of 60.1F and an upper limit of 79.2F.

Sensitivity Analysis: Comfort Load Factors and Parametric Studies

In order to provide more detailed information about comfort factorswe analyzed the heat flows in and out of the spaces, as well as the difference between the space temperatures and the ideal space temperature using a method described by Brown et al (2014). By comparing these space loads to the ideal temperature difference, it was possible to determine which loads were improving comfort and which loads were decreasing comfort. The comfort load factors in Figure 1 indicate the degree to which a particular load is pushing the temperature of a space towards the middle of the comfort zone or away from it.

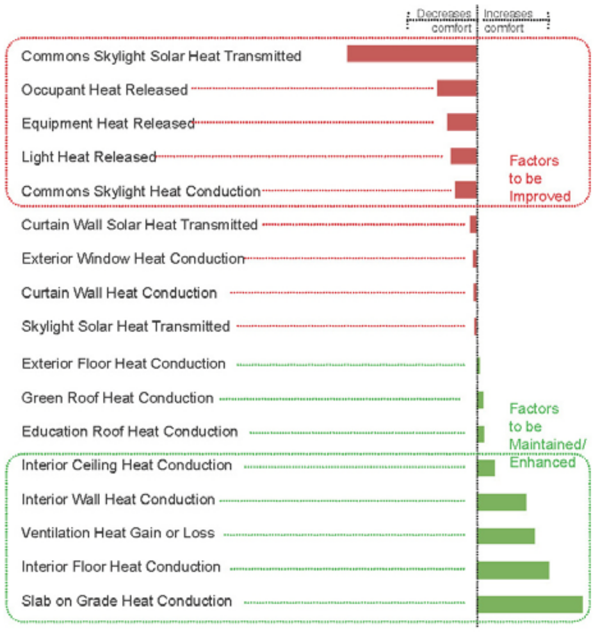

Figure 1: Summary of Comfort Load Factors (Police Station- Whole Building As Designed).

This comfort load analysis was used instead of elimination parametrics, an analysis techniqe broadly used to develop a better understanding of the energy use impact of each building component and factor in energy use. In elimination parametrics, a series of simulations set one component of energy use to zero at a time. When the results are viewed, a clearer picture of how the building uses energy emerges (Rosenbaum 2003). This requires running a relatively significant amount of models and displaying results in a way that allows the building modeler and the designer to review them, look for trends and draw conclusions to make useful design recommendations. In this project, by running a customized script on a single model as the quick analysis tool described by Brown N et al (2014), we obtained a quick overview of the factors affecting thermal comfort and established a list of potential strategies for the designers to consider

This sensitivity analysis provided a prioritization used to construct a customized suite of improvements that directly addressed the potential for overheating and extreme cold discomfort. The priorities included increasing natural ventilation, reducing internal heat from lighting, reducing the heat gain or loss through glazing areas and increasing the thermal mass effect. From these, results showed how much comfort can be improved relying only on passive strategies or building design decisions. Then, by parametrically modeling envelope improvements in an additive fashion the relative effect of each measure on overall energy use was also quantified. This step is essential to identify cost versus performance tradeoffs when a project inevitably reaches the value engineering phase.

Suite: Suggested design strategies to reduce energy consumption

We studied a variety of systems that could be deployed to reduce energy consumption. Our recommended suite was as follows:

1. Reduce equipment loads as much as possible. Choose efficient equipment and study the possibility of implementing a future DC power grid at the building level. Virtualization (desktop machines with applications and processing occurring on a virtual machine) also has the potential to both save energy and create a more manageable IT infrastructure in police facilities where computing resources often include individual desktop computers and on-site servers.

2. Daylight spaces that can be daylit and specify efficient lighting fixtures and control strategies to reduce electric lighting when daylight is available. This will reduce energy and demand cost and provide a more healthful environment for occupants.

3. Provide natural ventilation for as many of the spaces as possible. Further analysis is needed in order to size openings to achieve sufficient airflow by natural means.

4. Install occupant controlled openings, such as windows or vents that are directly controlled by the occupants of each space. Such openings may be manually controlled or controlled through the use of electrical or mechanical actuators under direct occupant control.

5. Ensure that the minimal ventilation required during the winter is provided by a system tempering the air to min 68F to prevent those spaces from becoming too cold once large groups of occupants leave.

6. Increase thermal mass effect by exposing the floor and ceiling concrete areas and doubling the layers of gypsum boards in the interior partitions. Attention must be paid to acoustical conditions when thermal mass is exposed. In contrast with the specified minimum requirements in envelope thermal resistance, there is no quantitative requirement in Standards, Codes, and Guides for building thermal mass (Wang et al, 2014).

7. Select glazing assemblies with a low U-value for large glazing areas. Prevent those facades from receiving direct solar radiation during the summer while still allowing some passive solar heating during the winter.

8. Redesign skylights to prevent solar radiation through the glass overheating interior spaces while still providing passive solar heating in the winter.

With these improvements, spaces in the suite model were comfortable three times more often than in the baseline model. However, the suite model showed that most spaces will still feel too cold from November to March, especially the ones with large window areas to the exterior. This confirmed the need for a mechanical conditioning system, even with all envelope and internal load improvements. This system would be used less often than in the current design as spaces were comfortable an average of 28.7% of the time, with the most uncomfortable spaces being those with the largest glazing areas facing southwest. Most office spaces were comfortable during an average of 39.2% of the year.

Net Zero Performance (ZNE)

The analysis for net zero performance focused on the baseline (as designed), the Suite that included all recommended technologies except the ones for equipment load reduction (#1) and the redesign of the skylight (#8), and the Suite with an extended photovoltaic (PV) array. The simulations provided an estimate of the total energy use and electrical demand of the whole building. Results for energy produced, energy used and net performance are summarized in Table 1.

The Suite model with natural ventilation, lighting and envelope improvements (glazing with lower U value (0.3Btu/ft²·°F·h), additional thermal mass and R-10 additional exterior wall insulation) with the same HVAC system had a total site energy use intensity of 60.5kBtu/sf/yr.

In order to achieve net zero performance, the project needs to generate as much energy as is used with on-site, renewable sources over the course of a typical year. Once the total energy use of the building under normal operation was quantified, simulation analysis focused on the energy production capacity of a PV array over the roof of the parking garage in order to study the annual net zero performance of the building using TMY3 Weather data.

Table 1: Net Zero Performance Summary

Energy Use Intensity (kBTU/sf floor area)			
	Baseline	**Suite**	**Suite + PVs**
Produced	36.3	36.3	47.2
Used	71.3	60.5	60.5
Net Performance	-35.0	-24.2	-13.3

Running weekly averages of energy produced to the energy consumed by the baseline building were compared. The net zero energy profile obtained by this comparison is represented in the orange areas in the graphs in Figure 2.

The PV array anticipated by the design team was insufficient to meet facility electrical needs for any given week of the year. The study then analyzed the net zero energy performance of two suites. First, we applied the envelope and lighting improvements (Figure 2, top graph). Second, we pushed the model further by including additional PVs (16,250sf). The annual net zero energy profile for these design alternatives showed an occasional surplus in electricity production from April to September and a clear deficit from October to March. In all scenarios, the PV array occasionally produced more than the building would consume (Figure 2, bottom graph, eg. midday on a typical July day).

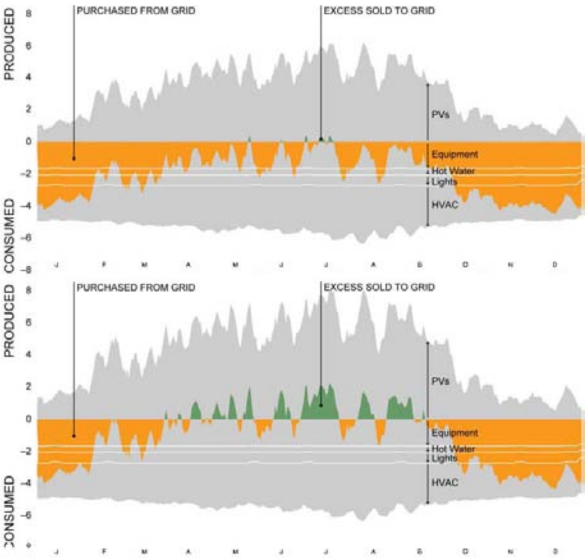

Figure 2: Annual Net Zero Energy Profile (MWh/day, weekly average) in two different design alternatives: with a suite of improvements (top graph) and with the suite of improvements and additional PVs (bottom graph).

Passive Survivability: Normal Operation

In essential services projects, it is necessary to identify and develop tools and metrics to support quantitative technical assessment (McAllister, 2013). The following analysis allowed the project to include the expected level of performance during and after a grid failure event as a priority goal.

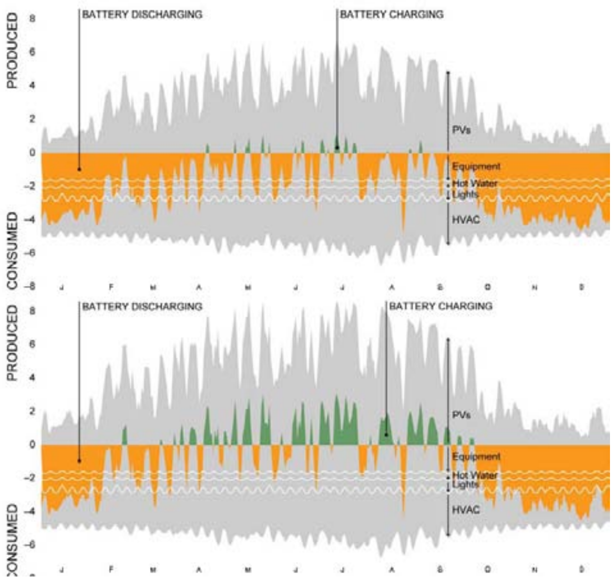

Figure 3: Annual 72-Hour Energy Performance (MWh/day, 3-day average) in two different design alternatives: with improvements (top graph), and with the suite of improvements and additional PVs (bottom graph).

To study passive survivability with respect to energy, the analysis looked at how long the facility could operate after being disconnected from the grid, relying only on PV panels and battery storage as sources of energy. Instead of looking at the building performance over the course of a typical year, this analysis provided more detail, focusing on the stated goal of 72hours of operation, during summer and winter weeks when a surplus and a deficit of the energy produced on site were identified in the annual net zero performance analysis.

First, this study assumed that the building maintained normal operation and full occupancy, to see what it would take for the facility to remain completely unaffected by an energy shortage during 72hrs. A running 3-day average was used to see the variation in the difference between energy produced and used for every 3-day period throughout the year for the Suite and for the Suite with additional PVs. This gave an initial indication of battery capacity requirements for initial energy storage required to supplement the PVs during grid downtime (Figure 3). The histograms in Figure 4 show the total number of 72hr periods for each battery size to store enough energy for the facility to use. To be prepared for any 3-day outage, about 13MWh of stored energy is required for the Suite with extra PVs. However, 4MWh of stored energy would suffice approximately half the time.

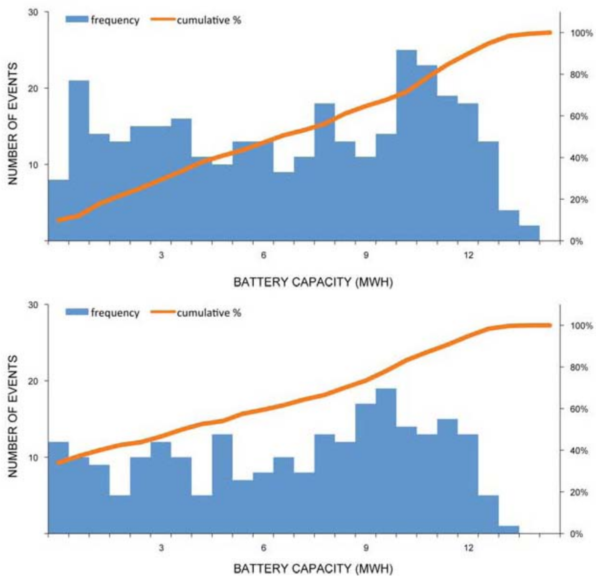

Figure 4: Battery Capacity (MWh) Requirements for 72-hr Events during normal operation in the suite with normal operation (top) and the suite with additional PVs (bottom).

To study this more closely, two extreme 3 day periods were compared: a winter grid failure event (around December 13th) when there is a large deficit in net electricity production and a summer grid failure event (around June 29th) when the facility has a surplus of energy.

During a winter grid failure event, the battery needs to have enough capacity to provide energy during 72 hours in order to supplement the energy produced by the PV panels. Also, the battery needs to be fully charged when the event happens. According to the graph in Figure 5, the energy use of the building in the December period is consistently higher than the solar energy produced. A battery capacity of 4MWh lasts less than a day, requiring the use of a diesel generator for the remainder of the outage.

This showed that normal operation during the winter is not possible for this extreme event with a 4MWh battery. Reducing the energy use of the building by prioritizing critical spaces and end uses would help the energy stored in the battery last longer. Increasing the size of the PV array would also help performance but requires a large effort to give any relatively significant benefit.

In the case of a summer grid failure event, the PV array consistently recharges the battery daily as shown in Figure 6, even when the building is in normal operation. It would even be possible to give some of that excess energy back to the grid or recharge batteries for other buildings or vehicles.

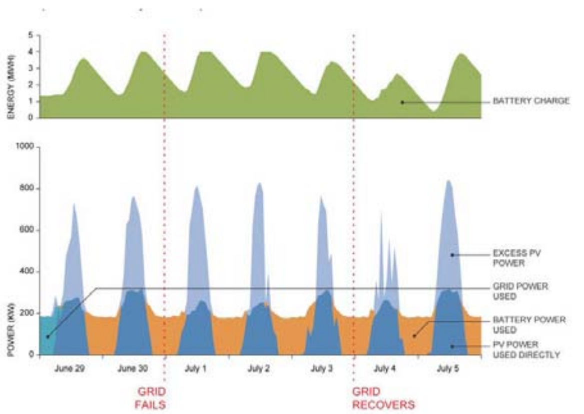

Figure 5: Facility Performance for Example of 72-hr Event- December (4MWh Battery + Suite of improvements).

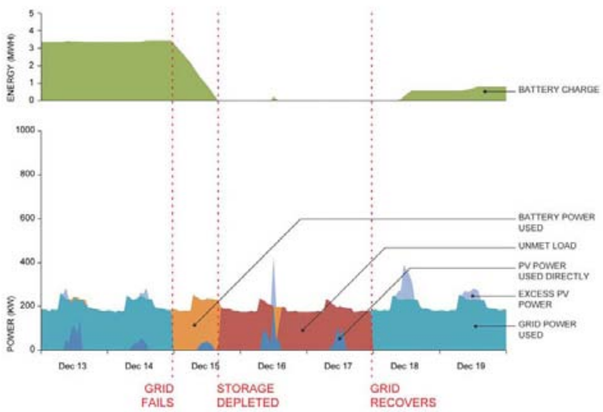

Figure 6: Facility Performance for Example of 72-hr Event- June (4MWh Battery + Suite of improvements).

Opportunities for energy use reduction during emergency situations

As a result of this passive survivability analysis showing that normal operation would not be sustainable in an emergency, several recommendations, in addition to increasing battery storage capacity and PV array size, were identified. These focus on reducing energy needs and shedding non-critical loads during extreme events.

- To reduce lighting energy use: identify lower-priority areas of the building that are not critical during crisis scenarios, such as training spaces.
- To reduce equipment energy use: most of the equipment in the building should still run and operate as usual. Only plug loads in training areas that are not critical during crisis scenarios could be shut down.
- To reduce HVAC energy use: occupants in fully conditioned buildings that cannot adapt their clothing levels have a relatively narrow constant range of comfort (68F to 74F) throughout the year. If occupant-controlled openings were provided (such as windows or vents that are directly controlled by the occupants of a space), and occupants had control over their clothing level (such as having the choice between a winter and a summer uniform), the temperature range for occupants to feel comfortable would vary throughout the year from a lower limit of 60.1F to an upper limit of 79.2F, according to the ASHRAE 55 - Adaptive Comfort Model.

If the HVAC is completely off in the spaces where those two conditions are met, so that they are not mechanically conditioned during an emergency, the Adaptive Comfort Model mentioned above is the correct method to describe how comfortable the occupants would feel in the building. Modeling results describe the ability of the building to remain comfortable for passive survivability purposes in order to identify spaces where HVAC systems can be completely turned off and thus save the energy typically used to condition those spaces.

In summary, spaces could be comfortable an average of 66.8% of the time, with the most uncomfortable spaces still being the ones with the largest glazing areas facing southwest. These are classroom spaces and thus most likely going to be unoccupied during an emergency. Most office spaces would be comfortable during an average of 85% of the year.

Sergeants and Lieutenants need to wear their vests even during an emergency and thus would not experience comfort within the requirements of the Adaptive Comfort Model. This is true even if the spaces they usually occupy show a real potential for being thermally autonomous with occupant-controlled openings and the suite of improvements included in the building design. Therefore, HVAC energy could potentially be reduced by selectively shutting down the systems on a zone by zone basis. The DOAS system could still provide breathing air without conditioning it (no tempering or dehumidification), and the radiant system would be only run for the spaces with no control over their clothing level.

The most difficult extreme events to deal with would be those that happen to occur during cloudy weather in the winter, when PV production is lowest. Load shedding is an important strategy to help in this situation.

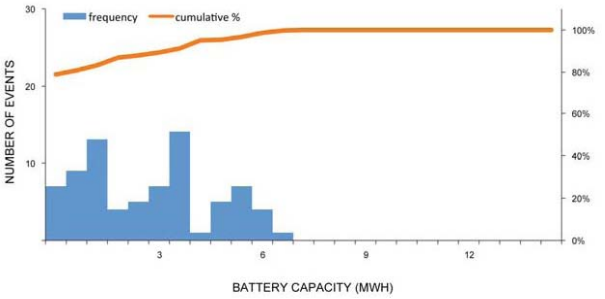

Figure 7: Approximate Battery Capacity (MWh) Requirements for 72-hr Event (Suite of Improvements with Reduced Operation and Additional PVs)

Results for the model including all strategies to reduce loads during an emergency show an Energy Use Intensity (EUI) of 37.2kBtu/sqft (reduction of 38.5%) and a greatly increased ability to sustain operations. In this scenario, 7MWh of stored energy in addition to PV output would meet the facility's 72-hr needs for 100% of cases we tested, as described in Figure 7. In about 80% of cases, this load shedding strategy scenario requires 0MWh of stored energy. In all cases, at least 2MWh of energy storage capacity would still be required to store excess energy from the day to use at night. Also, an initial minimum energy storage level is required in case the grid failure occurs when the PVs are not producing enough power for the building (eg, at night).

Passive Survivability: Reduced Operation

During a winter grid failure, reducing the energy use of the building through the load shedding techniques previously described is an important strategy for passive survivability. As shown in Figure 8, with load shedding, the 4MWh energy storage lasts much longer, resulting in about half of the 72-hour period being served by the battery and PVs alone. However, a diesel generator would still be required for the remainder of the outage.

A larger battery or complementary source of renewable energy (potentially wind energy) are the primary strategies to push this scenario to passive survivability for the full 72 hour period. Note that the period studied was one of the worst 3-day periods identified in the typical year data, so it does represent an extreme.

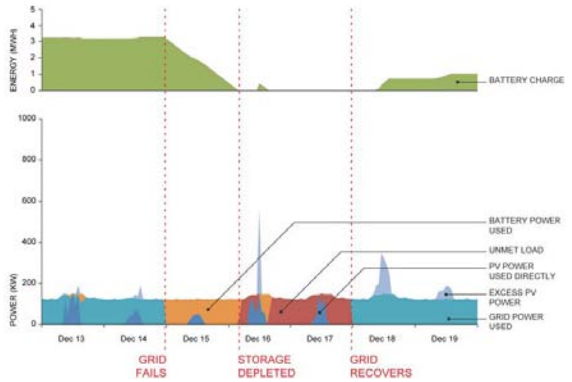

Figure 8: Facility Performance with reduced operation for Example of 72-hr Event- December (4MWh Battery + Suite of improvements+ Extra PVs+ Load Shedding).

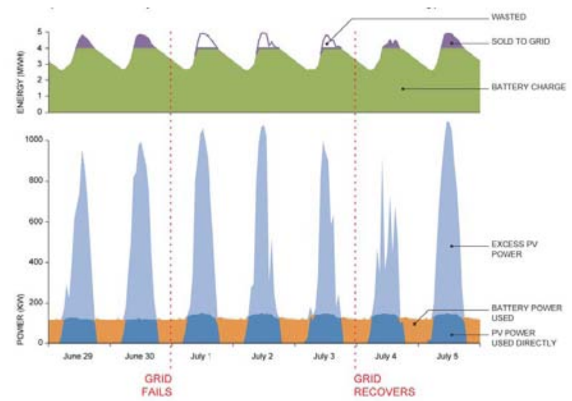

Figure 9: Facility Performance with reduced operation for Example of 72-hr Event- June (4MWh Battery + Suite of improvements+ Extra PVs+ Load Shedding).

During a summer grid failure (Figure 9), the PV array consistently recharges the battery daily, even when the building is in normal operation. It would again be possible to give some of that excess energy back to the grid or recharge batteries for other buildings or vehicles. During an extreme event, if no additional storage is connected (eg, electric car batteries), then this energy is wasted.

Design strategies for both annual ZNE performance and passive survivability

Similar to the hospital project, our study delivered recommendations and a description of various relevant energy systems that are integral to a holistic energy strategy (systems to produce energy, systems to store energy) to pursue both the annual net zero energy performance and passive survivability goals. Relying only on energy produced on site for a 72 hr period must include smart space planning, economic factors and performance in extreme events addressing comfort conditions and energy balance between generation, storage and use.

To Produce Electricity On Site: Deploy high performance photovoltaic panels to augment electrical supply during peak demand. Increase the PV array size to the largest feasible area, which we estimate to be about 73,000sqft by covering additional roof areas including areas designated for green roof.

To Store Enough Electricity On Site: Implement a battery storage system. This will increase power quality and smooth out the facility's electrical use, instantaneously responding to meet sudden spikes in electricity use and thus reduce demand charges. Note that for passive survivability we recommend having energy storage capacity of at least 2MWh.

DISCUSSION AND RESULT ANALYSIS

The simulation process used for both the analysis of ZNE performance and the potential for passive survivability was developed during early design phases, when the knowledge of how the design works could support the design team's effort to generate ideas and implement changes. Through the sensitivity analysis and comfort load factors, the design team gained a detailed understanding of how each of the main building components and operations would provide or remove heat over time. It also characterized whether this interaction would be helpful or not in the absence of a mechanical system, replicating an extreme event scenario.

Occupants in fully conditioned buildings that cannot adapt their clothing levels have a relatively narrow constant range of comfort (68F to 74F) throughout the year. In the case of the Police Station, the operative temperature was often below or above that comfort range even with a full set of envelope and internal load improvements.

Some spaces had strict requirements because of occupant clothing requirements or atypical metabolism levels. Due to these specific constraints, the potential measures suggested by these studies move the project performance closer to the goal of net-zero but were even more critical in optimizing passive survivability. Furthermore, no single system is adequate to meet both the annual ZNE performance and the passive survivability goals. Energy measures need to be considered as sets, or “suites”, to bring complementary and synergistic benefits that as a whole would meet the goals of the project. If the project didn't holistically consider these two issues, most improvements would not have been included in the design and thus, optimizing resilience during an emergency situation would have been more challenging, if not unfeasible, for this project.

The annual ZNE profile for the Police Station (Figure 2) showed that the Suite Design can obtain an occasional surplus in electricity production from April to September and had a clear deficit from October to March. In all design options considered, the PV array would occasionally produce more than the building consumes (eg, midday on a typical July day). This power could either be sold to the utility, or stored locally using battery storage.

Batteries are not only used for augmenting solar energy, they are also used to store excess energy produced during the day so it can be used at night. The analysis studied how this would work during normal operation and during extreme events by modeling the hourly interaction between PV production, building energy demand, and battery storage capacity. This highlights the importance of a well-considered control strategy, since batteries should be drawn down in order to make use of excess PV energy but, on the other hand, in the winter the batteries should maintain enough of a charge to sustain operations for an outage that could begin at any time.

The process of defining and analyzing ZNE and resilience goals and then contextualizing the implementation of photovoltaic panels and battery storage systems help stakeholders understand spatial and economic implications of pursuing these goals.

In this project, the passive survivability estimate covered purely the 3-day differences between energy production and use; additional consideration is needed to ensure coverage beginning at any time of day. For instance, even if the facility is net positive for a given 3-day period (Figure 3), if the outage begins at sunset, the facility needs enough initial stored energy to make it through the night until the sun rises the next day.

CONCLUSIONS

This paper extends existing work in the field addressing ZNE strategies and design for resilience in an integrated and holistic manner. Integrating such considerations is essential in mitigation of and adaptation to climate change.

The use of Thermal Autonomy as a design approach underlines the deficiencies of standard industry practice in evaluating building performance for passive survivability. For normal operation, the typical approach would be to model the building with a complete heating, cooling, and ventilation system. This would not evaluate the passive operation in those initial runs. The results would be presented as a bar chart of monthly energy use, abstracting the performance into a large amount of energy use. If subsequent climate-responsive strategies were modeled, the building loads would change, but the specific patterns, such as afternoon overheating, would not be apparent. For extreme events or resilience consideration, the goal would be to supply as much energy as the building is anticipated to use during normal operation using renewable resources and energy storage strategies on site.

If the issues of net zero energy performance and passive survivability were not approached holistically or early enough in the process, the recommendations for the design team would have varied and prioritized differently.

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