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CONSTRUCTION AND IMPLEMENTATION OF THE OFF-GRID ZERO EMISSIONS BUILDING

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ABSTRACT

This paper deals with the construction and implementation of the Off-Grid Zero Emissions Building (OGZEB), a project undertaken by the Energy Sustainability Center (ESC), formally the Sustainable Energy Science and Engineering Center (SESEC), at the Florida State University (FSU). The project involves the design, construction and operation of a completely solar-powered building that achieves LEED-NC (Leadership in Energy and Environment Design-New Construction) platinum certification. The 1064 square foot building is partitioned such that 800 square feet is a two bedroom, graduate student style flat with the remaining 264 square feet serving as office space. This arrangement allows the building to serve as an energy efficient model for campus designers in student living and office space. The building also serves as a prototype for developing and implementing cutting edge, alternative energy technologies in both residential and commercial settings. For example, hydrogen is used extensively in meeting the energy needs of the OGZEB. In lieu of high efficiency batteries, the excess electricity produced by the buildings photovoltaic (PV) panels is used to generate hydrogen via water electrolysis for long term energy storage. The hydrogen is stored on-site until needed for either generating electricity in a Proton Exchange Membrane (PEM) fuel cell stack or combusted in natural gas appliances that have been modified for hydrogen use. The use of hydrogen in modified natural gas appliances, such as an on-demand hot water heater and cook top, is unique to the OGZEB. This paper discusses the problems and solutions that arose during construction and includes detailed schematics of the OGZEBs energy system.

1 Introduction

The project described in this paper can be categorized broadly under Sustainable Housing, terminology that incorporates design principles that combine environmental, economic and societal consciousness, thus ensuring the longevity of not only the house but the environment in which the house resides. As the concept of sustainability and green have become a market, the definition and understanding of what is green/sustainable has started to vary. Market forces have stretched the definition so that ”green” ratings can be cheaper and more easily obtainable. Three years ago the Energy and Sustainability Center (ESC), formerly the Sustainable Energy Science & and Engineering Center (SESEC), at Florida State University (FSU) embarked on the design and construction of the Off-Grid Zero Emissions Building (OGZEB). The OGZEB, a vision of complete sustainability, uses two sustainable design frameworks that were selected due to their lack of influence from market forces, rather they are driven by a desire to be truly sustainable. These frameworks, that guided our efforts, were developed by Parris & Kates [1] and the U.S. Green Building Council [2].

Parris & Kates developed a sustainable development framework, and the U.S. Green Building Council has developed a

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Figure 1. The Off-Grid Zero Emissions Building

framework for measuring the overarching objectives; the benchmarks for the design, construction and operation of high performance green buildings that are provided under the Leadership in Energy and Environment Design (LEED) New Construction (NC). These frameworks consider everything from material selection to system designs, providing a broad based look at the sustainability of a building. With the LEED certification system in place, the housing construction industry is slowly adopting environmentally friendly construction materials, processes, activities and designs, thereby reducing the amounts of pollution and waste generated. The OGZEB brings all of these concepts together and looks at the integration of building systems to optimize energy consumption while also ensuring the building materials are as environmentally responsible and safe for the occupants.

When approaching a project of this scope it is critical to assemble a team to tackle the many issues and goals and insure that all are adequately met. The design and construction of this building encompasses several fields of expertise that are not typically required for the common building. A team of professionals and students was assembled to jointly design the house. The team consisted of a Mechanical Engineer/LEED Accredited Professional (AP), Innovative Architect/LEED AP, Structural Engineer, Electrical Engineer, Civil Engineer, Landscape Architect, Construction Manager, and an Interior Designer. An additional Mechanical Engineer, specializing in alternative energy, was included on the team to design the alternative energy systems. Each member of the team was drawn to the project by their environmental consciousness and desire to learn more about the LEED certification process.

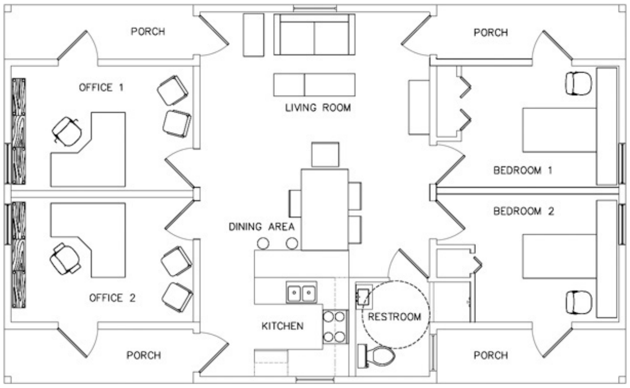

Figure 2. OGZEB Floor Plan

2 Background

For just over a year and a half the team worked to design a fully integrated building, the end result being the OGZEB. The OGZEB is a 1064 square foot Platinum LEED NC certified building [2], shown in Figure 2. The building is split into an 800 square foot graduate style flat and a 264 square feet of offices. The building is a living laboratory that is operating 24 hours a day. All the energy in the building is either converted from geothermal, solar thermal, or photovoltaic panels. This will allow research into new cutting edge technologies.

The first topic considered was the energy conversion method. In Florida, the primary sustainable energy resources are biomass, solar and geothermal (primarily used for heating and cooling applications). Of these three solar is the ideal solution for a single off-grid building. Most of the energy consumed by the OGZEB will be captured from the sun. A 6.9 kW solar array converts the sun's rays into electricity while 120 square feet of solar thermal panels will provide hot water and possibly, heating and cooling in the future. Excess electricity produced during the day is converted to hydrogen by a water electrolysis device. This hydrogen is then stored for nocturnal hours. When the house requires electricity at night a fuel cell uses the hydrogen produce electricity to power the house. The hydrogen is also used in thermal applications where it is more efficient to burn the hydrogen (80%) rather than use hydrogen to make electricity in the fuel cell and then power resistive heating (60%).

Due to the expense of these power systems it is extremely important to minimize the amount of electricity that will be used by the house. Energy efficiency considerations are key to reducing electrical consumption and started with the building envelope for the OGZEB. The building envelope chosen for the OGZEB was a Structural Insulated Panel System (SIPS) because of its higher total insulation and air infiltration reduction by up to 95% [3] over common framed structures. The reduction of air infiltration significantly improves the thermal comfort of a building allowing for more moderate thermostat set points. Other energy efficient design considerations were windows, doors, light shelves, and energy efficient lighting. The windows and doors have a U value of 0.24 giving them good insulative value while maintaining visual transmittance for day lighting effects. Light shelves are also used for daylighting by shading the building's occupants from direct light, and instead bouncing the light to the ceiling. This provides a top down lighting effect. When the daylighting does not provide enough light, a combination of Light Emitting Diodes (LED) and compact fluorescent lights illuminate the building. These lights not only consume less energy to provide the same number of lumens, but also emit less heat, thus reducing the amount of cooling required.

The last efficiency considerations were the systems of the OGZEB. The first system considered was the air conditioner. A geothermal heat pump was chosen. The system exchanges heat with the ground rather than the air, increasing the efficiency significantly. The system is also being integrated into the solar thermal system to increase the efficiency in the winter and the summer.

The second system was the water heater. This system is primarily supplied by the solar thermal system, but when the solar thermal system is not providing hot enough water, an on demand water heater, powered by the combustion of hydrogen, provides additional heat.

The OGZEB also uses water conservation techniques that reduce the water consumption of the building by over half. A grey water system was considered but modeling indicated that water consumption of the building was not high enough to warrant the system. The OGZEB has been designed and built to allow the incorporation of this system in the future if it is warranted.

The final consideration in the design of the OGZEB was the materials. Each material was considered for its ability to be recycled, recycled content, location of manufacturing, if its materials are rapidly renewable, and if the material off-gases any harmful gases. These considerations are important to not only reducing the impact of the OGZEB on the environment but also to increase the comfort of the building for the occupants. More information may be obtained regarding the design of the OGZEB in a previous ASME paper titled, ”The Off-Grid Zero Emission Building” [4].

In the past, most ultra sustainable or off-grid building designs never made it off the drawing board. The few that made it to construction ran into several issues depending on the level of integration and complexity.

Once the design is finalized it is time for construction. The following section describes the construction of the OGZEB and the problems/solutions that arose along the way.

3 OGZEB Construction

Construction of the OGZEB was very similar to that of the top of the line house using technologies that are not typical to all houses. The problems that arose during the implementation of technologies like the ground loop and the Structural Insulated Panel (SIP) system were common and expected. The truly unique components of the OGZEB, that required the most consideration, are the electrical production system, hydrogen storage system and the integration of solar thermal and Heating, Ventilation and Air Condition (HVAC) systems.

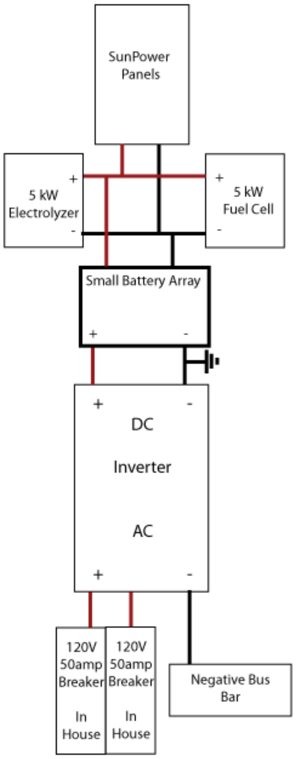

Figure 3. Initial Power System Design for OGZEB

The exterior and most of the interior were put together using common construction practices that emphasizing the use of sustainable practices, including recycling, choosing sustainable products and site management. When most of the structure of the OGZEB was complete the subsystems were installed.

3.1 OGZEB Electrical System

The Off-Grid Zero Emissions Building (OGZEB) electrical system consists of electrical production and power storage. Electricity for the building is produced by a solar panel array and a hydrogen storage system with a small battery array stores excess electricity for nights and cloudy days.

The original system design was for the solar panels, water electrolysis device and fuel cell to be integrated into one system that would then provide Direct Current (DC) electricity to one inverter. The inverter would then convert the DC power into Alternating Current (AC) power for the OGZEB. A schematic of

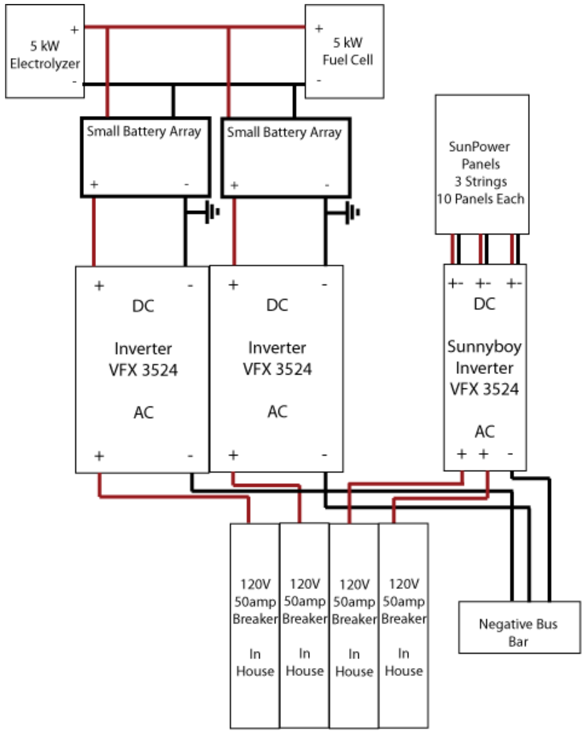

Figure 4. Final Power System Design for OGZEB

the original system can be seen in Figure 3.

However, in an effort to use the most efficient solar panels on the market, Sunpower panels were chosen to power the house. This caused a significant problem when it came to the integration of the DC power system. Sunpower modules are positively grounded while the rest of the components in the DC power system are negatively grounded.

3.1.1 Electrical Production

The Off-Grid Zero Emissions Building has a defined area for solar panels on the south facing and roof. SunPower (SPR-230) solar panels were chosen because of the high efficiency allowing more power production than typical panels. The panels were installed on the roof of the building and connected through conduit in an interior wall to the bottom of the house, wired into a SunnyBoy inverter. The solar panels were installed in three strings of ten panels to properly supply the inverter with power. The efficiency of SunPower panels is due to surface polarization as a result of positive grounding. The positive grounding causes significant problem when it came to the integration of the DC power system. Sunpower modules are positively grounded while the rest of the components in the DC power system are negatively grounded.

Several options were considered to fix this problem including dc-dc isolated power converters and dc charge controllers. Each of these systems that are currently available on the market still have grounding issues. In order to achieve a system that solved the problem, AC coupling was needed. The first attempt to design an AC coupling system was to use a Sunpower inverter to convert all of the electricity to Alternating Current (AC) and then back to DC. Most power converters could achieve this, but the Sunpower is a grid-tied inverter. The grid tied inverter requires AC power to turn on and synchronize and the typical converter does not provide this AC current.

The solution required the creation of a microgrid or AC coupling system using the Sunny Boy inverter and a inverter/charge controller. The inverter/charge controller will not only produce the AC needed to turn on the Sunny Boy inverter but also take AC power from the Sunny Boy and convert it to DC power that is negatively grounded. This allows the DC power system to be designed behind the inverter as seen in Figure 4. This is not the ideal system as there are losses in each energy conversion but these losses are minimal and currently there are no alternative systems available. The only inverter/charge controller that could accomplish this was the Sunny Island inverter. The Sunny Island inverter has a function call Frequency Shift Power Control that allows it to turn the Sunny Boy on in an off-grid setting. This setup still causes issues when the storage system is lower than 20%. At this level the Sunny Island will not operate long enough for the Sunny Boy to come online if there are any loads on the system. The building will need to be completely shut down until the Sunny Boy starts to generate power. This usually only lasts 5-10 minutes and the system controls have been modified to prevent storage levels from getting to a level that would cause this problem.

Two Sunny Island inverters were required for the house, each providing a leg of 120 volts, combining to power 240 volt equipment. The Sunny Islands also provided 48 volt DC current for the DC power storage system. The primary inverter synchronize the frequency of the power allowing the house to operate properly. Any discrepancy in the frequency or output voltage and they will not synchronize with the Sunny Boy inverter preventing it from coming online.

With the completion of the electrical production, storage is required to provide electricity to the building when the sun is unavailable. This system primarily uses hydrogen technology.

3.1.2 Electrical Storage

The original design of the storage system took excess electricity from the solar system and used it to split the water molecule. This hydrogen was then compressed using a gas booster and stored in compressed tanks for times that the sun was not available to provide energy for the building. When energy was required and the sun was unavailable the hydrogen would be combusted to provide heat or converted to electricity in a fuel cell.

The first aspect of the storage subsystem that was installed was the battery array. This array was installed to provide instantaneous power to the house. Most fuel cells come with this battery array to provide the power required to start the fuel cell and we added a secondary array that will be monitored to develop better control systems. This secondary system will be removed when the entire storage system is properly tuned. The secondary battery array was directly connected to the Sunny Islands and was used to get the solar system fully operational. After the solar system was fully commissioned, the fuel cell was added to the batteries and a current shunt was added allowing the Sunny Islands to monitor the charging of the batteries to insure that the proper amount of current was reaching the batteries. The fuel cell is a Plug Power 5 kW fuel cell and it was matched to the 48 volt system.

The final part of the storage system was the hydrogen combustion. Piping was installed to get the hydrogen to combustion appliances around the building. Due to funding constraints the hydrogen lines were originally installed with black steel. Hydrogen being a very corrosive gas, will extract carbon from the piping causing it to become brittle and possibly leak. These will be switched to stainless steel before the life span of the black steel has been reached.

4 OGZEB Thermal System

The solar thermal system was installed under the house along with the HVAC system. The solar thermal tank is 300 gallons of water that are pumped up to 120 square feet of solar thermal collectors on the roof to accumulate heat. There are two heat exchangers in this water, one supplies potable hot water for the house and the other supplies hot water for the HVAC system. The HVAC system was tied into the solar thermal system such that in the winter it provides heat to the HVAC. In the winter the water from the HVAC will cycle through the ground loop and then into the solar thermal system to increase the temperature of the water into the HVAC which will increase the efficiency of the unit. This integration of systems will vastly increase the efficiency and reduce electrical consumption.

The solar thermal/HVAC system will require a controls system to determine the best set point temperatures, ensuring the system is optimized. The optimization will determine what temperature will allow both systems combined efficiency to be the highest, reducing the total amount of electricity to be consumed.

5 Final Touches

With the power system and the interior taking shape, the finishes could begin. These included interior doors, plumbing fixtures, trim work, and lighting fixtures. The interior doors are solid core to reduce sound transmission between rooms. The plumbing fixtures are ultra low flow fixtures that were chosen to ensure that consumers would not be displeased using them and the toilet is a dual flush toilet allowing for the appropriate amount of water for the proper occasion. The trim package was salvaged from a building that was demolished on campus. The cedar was then re-milled and used throughout the house. This prevents more trees from getting cut down to make new product. Finally, the lighting fixtures and fans primarily use compact fluorescent bulbs but the can down lights in the living room and kitchen use LEDs. Light emitting diodes are still in their infancy. They are developing rapidly but they still have issues with providing light at distances, which is why they were used for location lighting rather than indirect lighting.

Figure 5. Hydrogen retrofit burner for the Solaire grill

5.1 Hydrogen Appliances

Appliances were the last addition to the OGZEB. The decision to use hydrogen as a fuel for heating appliances like the grill, water heater and stove; retrofit technology was designed that modified current combustion appliances, that use natural gas or propane, to burn hydrogen. The following sections highlight some of these systems and their retrofits. For additional information please refer to Sustainable Building Systems [5].

5.1.1 Grill The burner for the grill was designed to retrofit a Solaire Anywhere Portable Grill. To provide the optimal temperature distribution, the 90 degree orientation was chosen with the flames staggered and pointed at one another to allow the entire burner to ignite from a single point, as seen in Figure 5. The burner is made of two, 6.35 mm (0.25 in) stainless steel tubes with spaced 127 mm (5 in) apart. The total heating area of the hydrogen burner is equivalent to that of the factory burner. Orifices were drilled every 50.8 mm (2 in) starting at 6.35 mm (0.25 in) from the end of one burner and 31.75 mm (1.25 in) from the other. When the burner was assembled, the distance between flames was 25.4 mm, providing an even temperature profile.

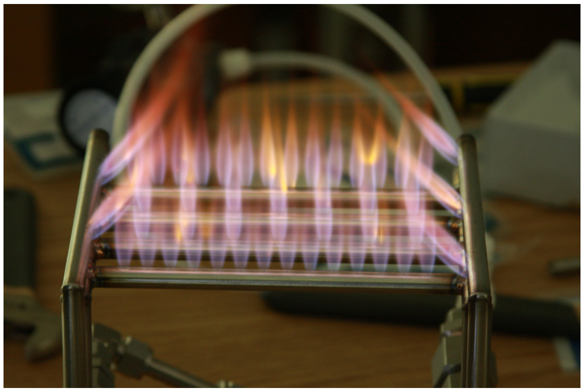

Figure 6. Hot water heater hydrogen burner

5.1.2 On Demand Water Heater

The burner for the on demand water heater was designed to retrofit a Rinnai C53 on demand water heater to combust hydrogen and heat water for the OGZEB. The OGZEB has a maximum hot water consumption of 7.57 lpm (2 gpm). The coldest water temperature is assumed to be 21°C with a desired hot water temperature of 41°C. These variables require 10.5 kJ/s of energy from the combustion of hydrogen. A hole size of 0.396 mm (0.0156 in) has a maximum flame length of 88.9 mm (3.5 in) which prevents the flame from contacting the heat exchangers, while providing a minimum of 0.25 kJ/s per orifice. A total of 52 holes are required to produce the total amount of energy for the system, assuming 80% efficiency. The burner is controlled by turning on and off four different sub burners that make up the complete burner. The sub burners were designed to be turned on and off in differing combinations to allow the energy output to be increased incrementally until all sub burners were on and producing 52 flames, as seen in Figure 6.

Each sub burner consists of 9.525 mm (0.375 in) stainless steel tubing with orifices drilled at even spacing. The first sub burner had four orifices that are aligned such that the flames are 45 degrees up from the tubes that make up sub burners three and four. Sub burner two has six orifices and the same 45 degree angle as sub burner one. Both sub burner one and two are pointed at the center of the burner. The 45 degree angle and orientation were chosen using Figure 7 due to the distributed nature of the heat gradient while not projecting heat further than 190 mm. Projecting heat past 190 mm would heat the wall of the burner cavity, causing thermal losses. The side burners also allow the entire burner to be lit from one location.

Sub burners three and four are fed by 12.7 mm (0.5 in) stainless steel tubing. Sub burner three has seven orifices on each 9.525 mm (0.375 in) tube while sub burner four has 14 orifices on each tube. Flames on sub burners three and four point straight up toward the heat exchangers. The design allows all sub burners to be lit simultaneously and only those not needed to be turned off.

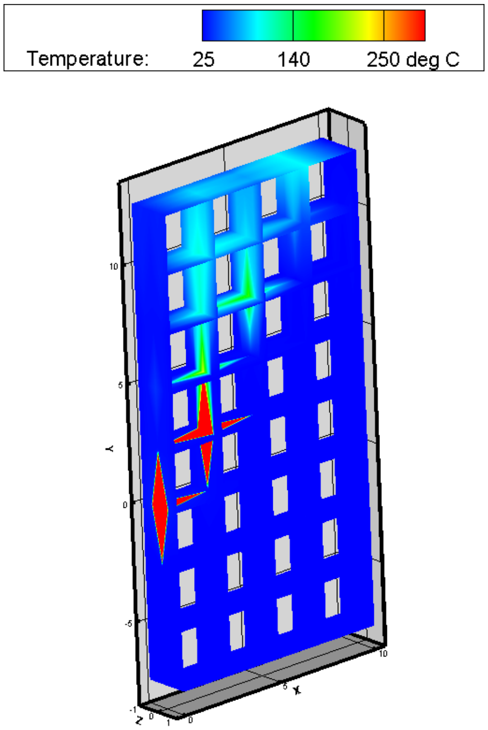

Figure 7. Three-dimensional thermal gradient: 0.396 mm orifice at 0.5 psig at 135 degrees

6 Conclusion

Sustainable design and construction has evolved significantly over the past few years as it has come into the lime light but there is still a lot of room for improvement. During the construction of this building it was determined that gathering the designers and builder to sit at the same table and actually discuss their designs and work together to overcome design issues can save a significant amount of time and money on problems during construction. Even though all of the planning reduced the number of problems that arose, a cutting edge design like the Off-Grid Zero Emissions Building will still have problems. The remaining problems have to be solved along the way but with some creativity and work there is no problem that can not be solved.

As sustainability has taken its place as a commodity, the market has been flooded with new technologies. These technologies range widely from the extremely sustainable and expensive to the cheap, that only give lip service to sustainability. It is the goal of this building to point out the difference and provide the public with a testing ground for technologies that will give you a cost/benefit ratio analysis for each technology. The OGZEB will not only educate the public about the best practices for building sustainably but also what appliances, lighting and other technologies they should use to achieve the best cost benefit ratio.

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