LCA of a designed single-family housing in Atlanta under two different energy usage systems

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Abstract - According to the United Nations Environment Program (UNEP), 87% of the US population will be living in urban areas by 2030 which brings in an increasing demand for residential buildings in metropolitan areas all over the US. High performance houses and net zero house which equipped with photovoltaic (PV) panels are among new generation of buildings emerging and rapidly growing in real estate industry. This study presents the comparison results of an environmental Life Cycle Assessment (LCA) on a pre-designed high performance single-family detached building with a net zero type of it in Atlanta, Georgia. The study covers both embodied and operational energy usage and material of construction, operation, maintenance and demolition phases of the buildings over 70 years of its life span. The relevant Life Cycle Inventory (LCI) was conducted from the project designed by Georgia Tech "High Performance Building" group for the US Department of Energy (DOE) "Zeroes" competition and the LCA software tool, SimaPro, was used to perform the Eco-Indicator 99 impact assessment method. The results indicated that although there are significant energy savings due to the implementation of PV panels, the impact of human health and environment damage, such as carcinogenic effects, radiation damage and mineral resource depletion involved with these technologies which are not usually considered, is highly related to the primary resource of the power generation. Additionally, the environmental and economic damages of a backup battery and the grid stability are other important issues which will eventually arise by the increasing number of high performance and net zero energy buildings.

Keywords: LCA, Residential, High Performance House, Net-zero House, PV, Environmental Impacts

1 Introduction

According to a recent report from Washington Post, the detached, single-family houses are far and away the most common style of housing in major American cities. More specifically, based on new 2014 American Community Survey data on the characteristics of occupied housing, almost 40% of the homes in Atlanta are single family detached houses.

A residential building utilizes a variety of building components in its assemblage designs. The assemblages involve a complex arrangement of material fabricated with various technologies, meeting legislative requirements. The assemblages are produced from a wide range of resources using energy intensive processes, from raw material extraction to final disposal. Energy intensive processes consume a large amount of resources for the generation of power, and produce significant emissions and solid waste. The environmental impacts associated with building assemblages also include operational use of the residence with its heating and cooling, as well as their maintenance and disposal. These systems also have a significant economic cost and social effects. Assessing the environmental impact and cost of a whole building over its lifetime and its' social effects is a complex exercise, as it requires assessment of all its elements and life cycle stages. Life cycle assessment (LCA) approach evaluates the life cycle environmental impacts, life cycle cost and life cycle social effects, respectively [1].

The LCA has been studied in multiple climate zones ranging from hot and humid India to extremely cold Michigan. The energy consumption of the building should include initial embodied energy, operation energy and maintenance energy [2]. A comprehensive LCA analysis on residential houses could be used to make informed budget decision or market purposes [3]. As the PV panel installation get more attention from both public and private sector, it is crucial to analyze economic value, energy conservation and environment impact of the PV panels by integrating it into LCA of residential house [4]. The quality of the input and output data is important to evaluate the result, as such, the SimaPro provides reliable and useful database and result of LCA [5].

This report focuses on all three goals of sustainability which are environmental, economic and social aspects of two residential buildings in Atlanta. The tools, frameworks and processes of LCA of buildings are discussed in the next. The limitations, gaps and assumptions are identified and summarized as well.

Finally, the results, and pros and cons of each type of building is discussed and negotiated.

2 Life Cycle Assessment

Performing an LCA is one way to assess the impacts a product has on the natural environment. The International Organization for Standardization (ISO) has developed international standards that describe how to conduct an LCA (ISO 14040 series). An LCA is a study of the environmental aspects and potential impacts throughout a product's life—from raw material acquisition through production, use and disposal [6]. The ISO standards describe three phases of an LCA. The first phase is an inventory of the inputs and outputs of a product system. The second phase is the assessment of the potential environmental impacts associated with those inputs and outputs. The third phase is the interpretation of the result of the inventory analysis and impact assessment phases in relation to the objectives of the study. These three phases are commonly referred to as (i) life cycle inventory analysis, (ii) life cycle impact assessment, and (iii) life cycle interpretation. In this report, "LCA" will refer to all three phases [7].

2.1 Goal

The purpose of this project was to determine whether a net zero single-family house has an overall environmental, economic and social advantage over a high performance house in Atlanta. It should be an energy conservation guideline for the future residential house. To achieve this goal we used life cycle inventory data to conduct a life cycle assessment of two kinds of houses: net zero house, high performance house equipped with PV panels; the other would be a high performance house using electricity from the power grid.

2.2 Scope

The functional unit in an LCA is defined in ISO 14040 as the quantified performance of a product system [8]. In this case, the functional unit is one house. The system boundary is the interface between a product system and the environment. The system boundary of this study is shown in Figure **1**. It includes the inputs and outputs of energy and material from construction, occupancy, and maintenance. The system boundary excludes human resources, infrastructure, and accidental spills, impacts caused by people, and decomposition of household components after disposal.

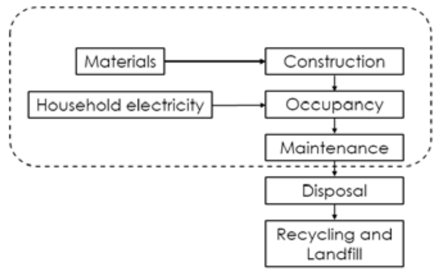

Figure 1 System boundary for house Life Cycle Assessment

The same layout is assumed for both the high performance and the net zero houses. These houses were designed by Georgia Tech "High Performance Building" group for the US Department of Energy (DOE) "Zeroes" competition and all the inventory and materials was extracted from their documents. More detailed description about the buildings and their characteristics are presented in the following section.

2.3 Impact Assessment Methods

The aim of the impact assessment of LCA is to evaluate and assess the importance of the environmental impacts of the two building systems in this study. There are ten main environmental impact categories applied in this research including impacts to human health (carcinogens, respiratory organics and inorganics, climate change, radiation and ozone layer), impacts to ecosystems (eco-toxicity and acidification/ eutrophication, land use) as well as impacts to resources (minerals).

In this project, Sima-Pro was used as the LCA software to analyze our data inventory. Sima-Pro was developed by PRé Environmental Consultants to conduct various steps of the environmental impact assessment simulations with the purpose to perform LCA calculations. In this study, the Eco-indicator 99 system method was used to interpret and weight the LCA results.

3 Methodology – House Description

3.1 Basic Information

The project is a 3 bedroom single family detached residential house assuming that a couple and their future children are using in for its 70 years of life span.

As mentioned earlier, we have developed environmental life cycle inventory data to evaluate the environmental aspects of a high performance house versus a net zero house.

Each house has the same layout but only net zero house is modelled with PV panels. This paper presents a comparison between the designed high performance building and the net zero house of its type.

3.2 Material Flow

The general concept of material usage in this design is to unify the type of material in building, improve the insulation level without compromising the affordability. Both houses are designed in the same method and materials, which could eliminate the differences caused by design. With this design, the base house already reaches a decent quality compared to an average single family housing in current market.

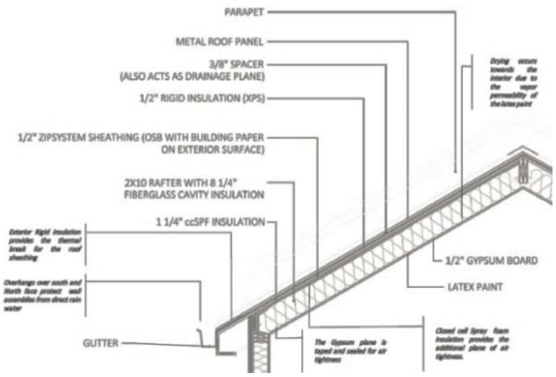

Figure 2 Cross-sectional view of the roof

The design concept is to design a compact roof consisting of a metal panel over an unvented ceiling. The roof ridge is oriented east west and the sloping plane is north-south. Larger portion of roof faces south so that it can receive more solar panels [9]. All the joints in the gypsum board are specified to be taped and sealed. The joint where the roof meets the wall is also taped to maintain the continuity of the interior air barrier. The air sealing is further reinforced with one inch of closed cell spray foam insulation underneath the sheathing. This helps in preventing moist indoor humid air to reach the underside of the roof sheathing where condensation can occur [10].

The roof sheathing is a ZIP System that comes preinstalled with house wrap with optimum permeability, which allows for vapor diffusion to the exterior side. The roof achieves a total thermal resistance of R-41.75 with an R-30 8.25 inch fiber glass-batt cavity insulation and 1.25 inch closed cell spray foam insulation within 2x10 rafters, and 0.5'' XPS board R-3 on exterior sheathing. The half inch XPS rigid insulation controls the thermal bridging that could occur between the sheathing exterior roof panel and the sheathing.

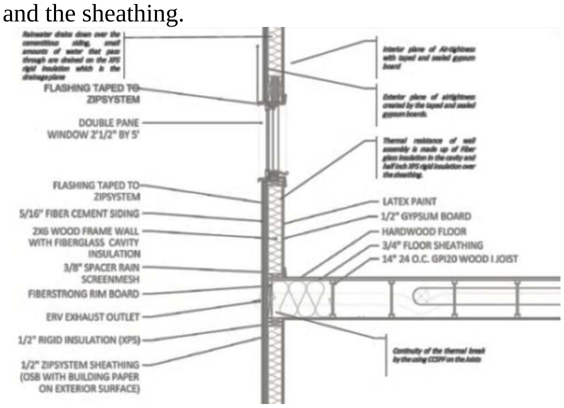

Figure 3 Cross-sectional view of the wall

The design team employed Mixed-humid House Design as introduced in Building Science Corporation [11] as the wall assemblies in this design. The exterior surface of the wall uses the bulk water "source control" strategy. Polyethylene flashing as show in figure 7 installed at horizontal joints to ensure no seepage occurs between those joints. The wall assembly is designed to be air tight from the inside plane of the Gypsum board. Like the roof, the joints of the gypsum board is sealed with taped to make it air tight. All electrical penetrations are sealed to the board. An exterior plane of airtightness is created using taped and sealed rigid insulated sheathing reducing issues with wind washing. Our 2x6 wood advanced frame walls achieve a nominal R value of R-22 using fiberglass cavity batt R-19; 0.5'' XPS board R-3. The XPS rigid insulating sheathing is added to elevate the temperature of the first condensing surface (inner surface of the ZIP system) to reduce the risk of condensation occurring within the assembly. Winter months require lower humidity levels within the spaces to prevent moisture diffusion through the wall assembly. During summer months vapor drive will primarily be from exterior to the interior.

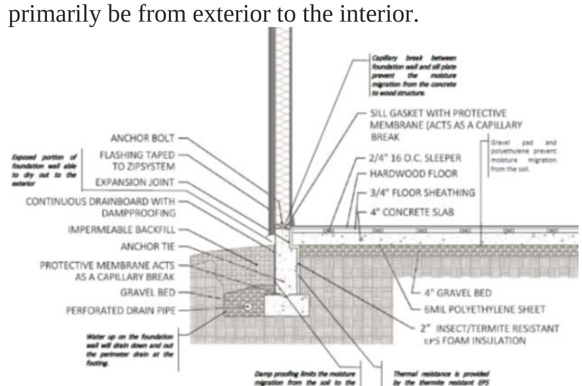

Figure 4 Cross-sectional view of the foundation

The foundation stem walls are cast in place. An impermeable layer of soil is installed next to the foundation to prevent bulk rainwater to flow into the soil. Any amount of water against the stem wall of the foundation is allowed to flow down to drain off into the perimeter drain installed at the footing. This wall is dam proofed to prevent liquid water to flow into it. Moisture migration is controlled between the floor structure and the foundation with the installation of a capillary break on top of the sill plate. A 4-inch deep, ¾ - inch stone bed functions as granular capillary break below the polyethylene. Sill gasket with protective membrane is installed between the floor plate and top of the foundation stem wall.

The stem wall is able to dry out to the exterior through the exposed portion above grade. For exterior soil moisture, the damp proofing on the foundation walls is used to control moisture migrating from the soil into the foundation.

The thermal resistance to the concrete slab is provided by the 2 inches EPS rigid insulation. This comes with a borate coating which prevents insect issues. A thermal break is maintained between the stem wall and the concrete slab using the same.

As it is more clearly states, the whole building is constructed by wood (pinewood, plywood and OSB), and fiber glass for insulation. The usage of concrete and steel are minimized to alleviate the environment impact from material usage. To ease the input process in Sima-pro, we categorize the material inventory as below.

3.3 Energy Usage

The energy usage of these two houses in their 70 years' life span is one important input for life cycle assessment as well as the material flow. For this two houses particularly, all of the energy consumed in the house is coming from electricity.

For the two residential houses, electricity usage can be simply divided into three categories: appliance usage, heating usage and cooling usage. Based on the energy simulation result of the house model, the heating season can be simplified as from October to March and cooling season is from April to September. There are two assumptions in the model: first, only 2.2 people averagely living in the house in the 70 years period and people normally will not be at home during the daytime. During the heating season, the heating load is calculated by subtracting the appliance usage from the weather-related load. On the contrary, the cooling load in the cooling season is estimated by adding the appliance usage from the weather-related load. The appliance electricity usage, heating load and cooling load is obtained from the energy simulation result of the house model.

3.4 Assumptions of Building Load

During a 70 years period, many factors could effect on the house performance. Some basic assumptions are setup to make the model more dynamic. For the house load, the weather-related load is assumed to increase 1% per year since the infiltration efforts and heat loss of the house will increase along with the aging of the house. Secondly, the performance of the house is estimated to improve to the initial stage after the renovation which will occur after 35 years and then the weather-related load will vary based on the assumption 1 in the second 35 years. Thirdly, the appliance load is assumed to increase 2% every 5 years since more equipment will be brought into the home along with the development of technology. The electricity consumed by appliance will also go up correspondingly even the equipment is expecting to operate more efficiently. The detail information is shown in Table 1.

Table 1 Assumptions of building load

Item	Assumption	Reason
Weather-related Load	Plus 1% per year	House aging problem
Appliance Load	Plus 2% per 5 year	Add more equipment
Retrofit	The thermal load drops back to new house level	Replace floor, ceiling, insulation, windows, etc.

3.4.1 Assumptions of HVAC System

The HVAC system is same in the two houses. Based on the design value, the high performance HVAC system can reach a Seasonal Energy Efficiency Ratio (SEER) at 17.8 and a HSPF at 10.7. Additionally, based on the average life span of HVAC system, we setup the life span of HVAC system as 20 years and the HVAC system will be replaced every 20 years. In the entire life span of the house, the HVAC system needs to be replaced 3 times. Besides the equipment initial information, we also make an assumption to estimate the performance of HVAC system in the next 70 years. The detail information is shown in Table 2.

Table 2 Assumptions of HVAC system

Assumptions of HVAC system		
Efficiency	Drops 1% per year	HVAC aging problem

3.4.2 Assumptions of PV panels

According to the house design, the model of designed PV panel is OPT 280-60-4-100, produced by Sunvia®. The product information is shown in

Table 3. Based on weather data of Atlanta area and the amount of building electricity consumption of the first year which we obtained from energy simulation, 18 pieces of the PV modules can provide enough electricity to satisfy the house for the first year, and the annual electricity generation capacity will be 7267.82 kWh [12]. Based on the 80% power output warranty period, we estimate the life span is 25 years. In the entire life span of the house, the PV panels need to be replaced 2 times.

Table 3 PV panel product information

PV panel information	
Power Classification (Pmax)	280W
Module Efficiency (%)	17%
Type of Solar Cell High-efficiency ARTisun Select cells of 156 x 156 mm (6 in.)	Type of Solar Cell High-efficiency ARTisun Select cells of 156 x 156 mm (6 in.)
Cells / Module 60 (6 x 10)	Cells / Module 60 (6 x 10)
Module Dimensions 1652 x 982 mm (65.04 x 38.66 in.)	Module Dimensions 1652 x 982 mm (65.04 x 38.66 in.)
Operating Module Temperature -40°C to +85°C (-40°F to +185°F)	Operating Module Temperature -40°C to +85°C (-40°F to +185°F)
80% Power Output Warranty Period	25yrs
90% Power Output Warranty Period	10yrs

To calculate the power generation in the 70 years period, several assumptions are established for the PV system, which are shown in Table 4.

Table 4 Assumptions of PV system

Item	Assumption	Reason
Efficiency	Power output drops 5% per 5 years	Aging problem
Replacement (every 25 years)	The efficiency increases to the initial efficiency	New product

Based on the assumptions of the building load and energy systems, the total electricity consumption trends are shown in Figure 5. From the figure we can find that PV system cannot provide enough electricity after the first several years which mainly because the increase of the electricity consumption and the decrease of the PV generation efficiency.

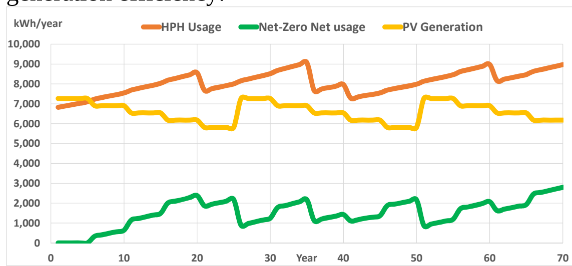

Figure 5 Electricity consumption trend in 70 years

For the high performance house, all of the electricity comes from the electricity grid. For the net zero house, the electricity from the grid is the gap between the house electricity consumption and PV generation. Based on our calculation, the high performance and net zero houses consume the delivered electricity are 564,599kWh and 104,625kWh in the entire 70 years.

4 Result and Discussion

Based on the data we gathered from the house design and the calculated result of the energy consumption, a final inventory in Sima-Pro is shown in Table 5. The inventory includes the total material input during the building construction period and the entire operation and maintenance period. The amount of the material includes the material used for the retrofit and equipment replacement. Georgia electricity generation by resource from EIA is shown in Table 6

Table 5 Final Inventory input in Sima-Pro

Materials/Assemblies/Processes	Quantity	Unit
Material inventory of the basic house model		
Concrete (reinforced) I	5610	kg
Fe360 I	156.51	kg
Pine wood, timber, production mix, at saw mill, 40% water content DE S	8921.63	kg
Plywood, at plywood plant, US PNW/kg/US	15946	kg
Oriented strand board product, US SE/kg/US	3584.4	kg
Glass fiber I	224421.2	kg
Iron and steel, production mix/US	928	kg
Vinyl chloride, at plant/RER S	48184	kg
Vinyl fluoride, at plant/US S	368.18	kg
Flat glass, coated, at plant/RER S	364.2	kg
Concrete roof tile, at plant/CH S	9562.5	kg
Gypsum plaster (CaSO4 alpha hemihydrates) DE S	17.76	kg

Materials/Assemblies/Processes	Quantity	Unit
Galvanized steel sheet, at plant/RNA	288.65	kg
Paint ETH S	40.86	kg
Sealing tape, aluminum/PE, 50 mm wide, at plant/RER U	74000	m
N-olefins, at plant/RER S	850	kg
Copper tube, technology mix, consumption mix, at plant, diameter 15 mm, 1 mm thickness EU-15 S	74	kg
Refrigerant R134a, at plant/RER S	28	kg
Loader Operation (one tractor)	2	month
Net zero house special material inventory		
Photovoltaic panel, single-Si, at plant/RER/I S	90	m2

Table 6 Georgia electricity generation by resource

Resource	Percentage (%)
Gas	43.76
Coal	15.14
Nuclear	33.03
Hydro	3.72
Other	4.35

4.1 Environmental Aspect

To analyze the environmental influence of the two houses, we need to consider the issue from three categories: the impacts on human health, the impacts on ecosystems and the impacts on resources.

Figure 6 shows the comparison result of damage assessment for the two houses. From the comparison, the high performance house has a better performance on Eco-toxicity, Land use, Minerals. Meanwhile, the Net-Zero house has significant less damage on Carcinogens, Respiratory organics, Respiratory Inorganics, Climate Change, Radiation and Acidification/Eutrophication. From the relative percentage result we cannot tell which house has an absolute better performance since neither house performs better in all indicators.

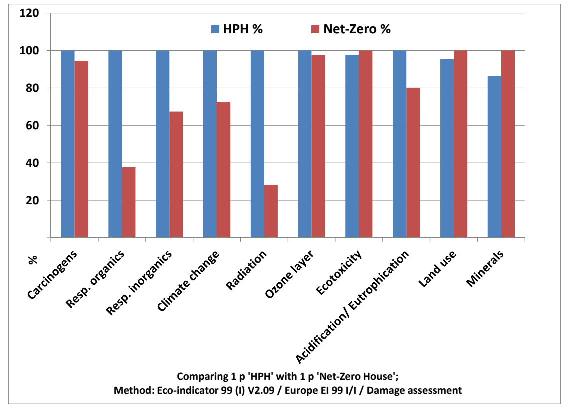

Figure 6 Comparison of damage assessment for the two houses

Figure 7 shows the comparison result of single score. The result shows that comparing with the impact on ecosystems and resources, the impact on human health take the most weighted portion for both houses. And the net zero house has a better performance than the high performance house in this category. The impact on human health should be the priority concern in the comparison since it takes much more points than other two categories.

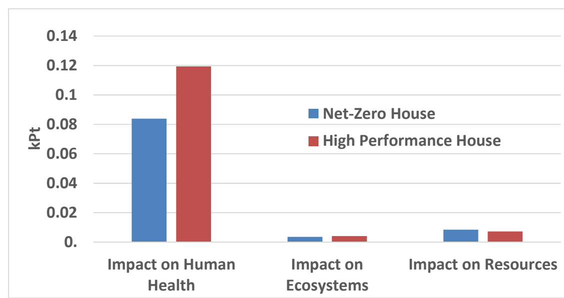

Figure 7 Comparison of single score result

To analyze which indicator has the most impact on human health, the Figure 8 and Figure 9 are developed which shows the single score result of the high performance house and the net zero house. The results show that the climate change and respiratory inorganics are the top two indicators which impact on human health.

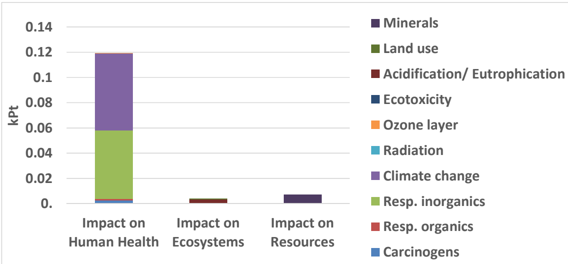

Figure 8 Single Score result of high performance house

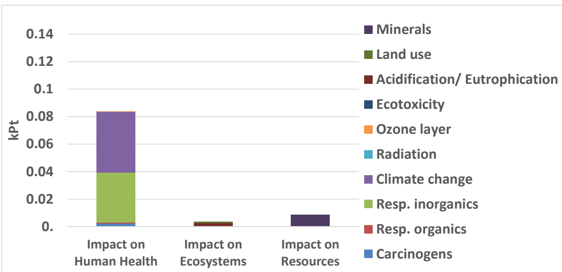

Figure 9 Single Score result of net zero house

Furthermore, the normalization result we got from Sima-Pro tells which material/energy input in the entire life of the house has the most impact on human health. Figure 10 shows that the delivered electricity and glass fiber has the most impact for human health, which mainly effects on respiratory inorganics and climate changes. Figure 11 shows that delivered electricity has much less impact since the total usage in the net zero house is much less than the grid electricity usage in the high performance house.

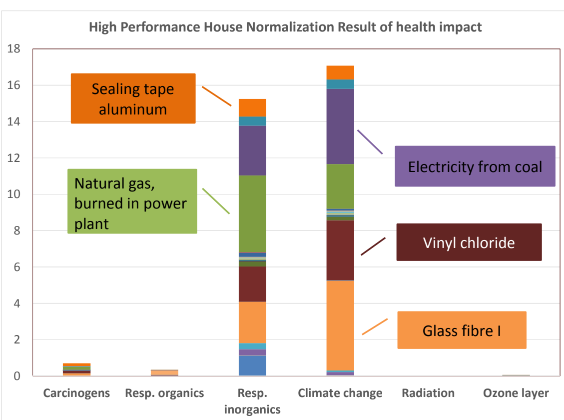

Figure 10 The normalization result of health impact of the high performance house

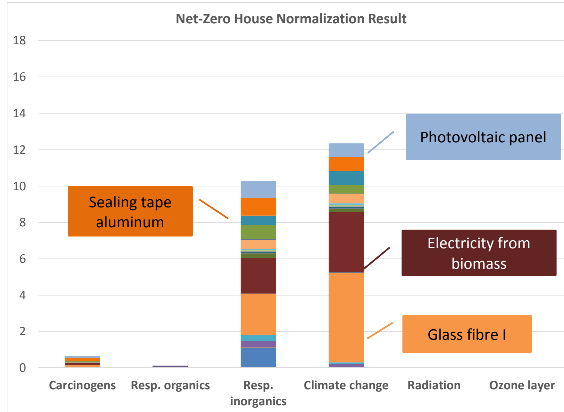

Figure 11 The normalization result of health impact of the net zero house

4.2 Economic Aspect

To simulate the economic perspective of the project, we made several assumptions. The price of electricity on average in Atlanta is 12 cents per kWh and has 3.6% annual increase in next 70 years based on the energy price increase trend in Atlanta. We assume the inflation rate could be stable at 2% during the research period. Based on the warranty information and typical model, the power output of PV panels drop 5% every 5 years, As a result, the PV panels will be replaced every 25 years as well as the HVAC system will be replaced every 20 years based on the information of the life span. As the technology make profess gradually, we assume the efficiency of HVAC system will increase by 5% by next replacement.

The present value of initial cost of net zero energy house is $7,378 higher than the high performance house due to PV panel installation, but the operation cost of the net zero house is significantly lower than a regular high performance house. With a payback calculation, the PV panels on the house could be pay back within 7.82 years without inflation rate and 8.37 years with 2% inflation. One important factor here is that the PV panels have 30% of total system cost incentives from the federal government with the policy of encouraging people using renewable energy, which directly reduce price of the PV panels from $10,540 to $7,378.

From this perspective, the usage of PV panels are beneficial for residences since it save money on energy usage over a long period of time, but it might not be as appealing to builders and contractor since the initial cost are what they are mostly concern.

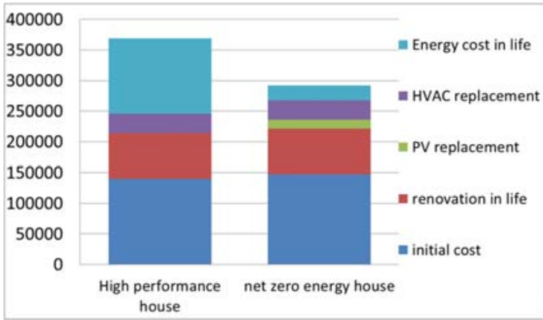

Figure 12 Life cost comparison between the two cases

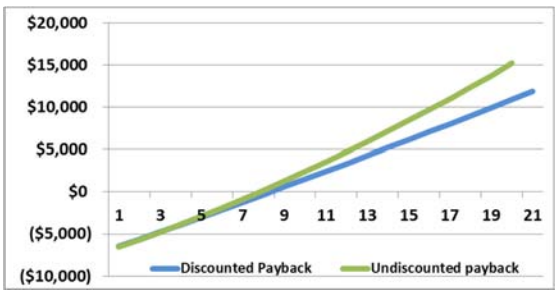

Figure 13 Pay-back year analysis of PV panel

4.3 Social Aspect

We have already covered the environmental and economic aspects of sustainability of these two houses. However, as mentioned before, besides the ecological impacts, there are multiple impacts that are relative to the social environment when new technologies are adopted. In this part, we briefly went over different social aspects of the PV system we have used in the net zero house structure.

4.3.1 PV panels

1. Increase consumer choices: In this case, at least consumers will have choices to choose the electricity resource for their building usage. Hence, the environmental lovers will have the chance to adopt a renewable energy technology for their building's energy systems.
2. Energy independence and security: The more that we reduce the energy consumption of our buildings; the less dependent we are on fossil fuels and foreign sources of energy. Ultimately, this increased independence and security supports peace and prosperity.
3. Significant potential of savings from electricity: Increase potential spending on other aspects of living: leisure, entertainment, etc.
4. Protect communities throughout the supply chain of PV industry and recycling operations
5. Family Wage Jobs: Need to employ highly skilled craftspeople and technicians, which support family wage jobs.

4.4 PV Reuses

As people are focusing more on renewable energy and the technology of PV technology getting more mature, the PV usage has been growing steadily in the past decades. It also brings a new issue of recycling and reusing aging PV panels. As the previous study shows that PV panel generation are energy intensive and create a quite heavy environmental burden. To solve this problem, a recent study has published a promising solution and analysis [13].

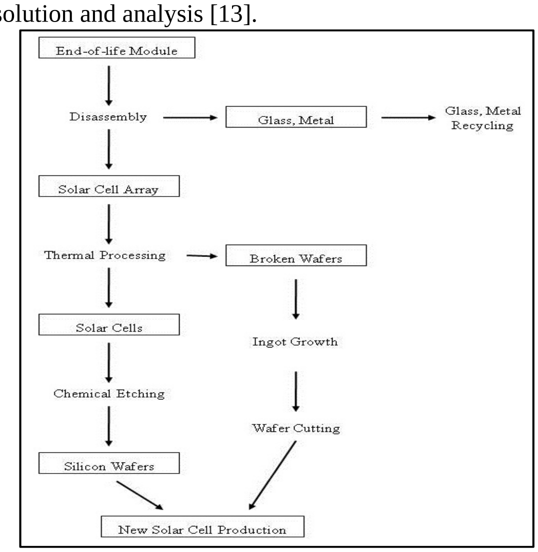

Figure 14 The flow chart for PV panel recycles

The research has stated that the end-of-life module could be disassembled and reused in new solar cell product with a series of process. The important breakthrough of this technique is the energy saving throughout the process. The brand new PV modules need 306 kWh while the recycled modules consume 0 kWh. To recycle the end-of-life module, it only consumes 92 kWh energy which is around ¼ of using new modules. The most prominent advantage of recycled modules is it generate the same amount of energy as the new modules

Table 7 The cost comparison between new wafer and recycled wafer

	modules with new wafter(kWh)	modules with recycled water(kWh)
wafter production	306	0
recycling process	0	92
cell processing	45	45
Module assembly	49	49
Total	400	186
Energy generation	K120(kWh/year)	120(kWh/year)
EPBT	3.3	1.6

5 Conclusion and Future Research

The comparison of the 2 different energy usage systems could be concluded from three aspects. The net zero housing currently is apparently appealing based on current Georgia electricity generation resource distribution, which mainly affected the climate change and Respiratory inorganics. The net zero housing option uses less energy from the primary resource and alleviates the environmental impact from this perspective. From economic perspective, the net zero housing has a more obvious advantage to residences with a roughly 8-year payback period per installation. The 30% incentives from the federal government is a major factor of reaching these benefits. It clearly shows how the power from the policy level could influence the decision making of energy usage. From social level, the net zero housing improves the health condition even from a macro scale, and improve the quality of air and human health. Also, by promoting the renewable energy usage, it could bring up public awareness to the environmental issues and sustainability.

There are several concerns not brought up in this research. The energy storage is not considered, if the house is responsible to store the excessive energy generation, the space usage, and battery production could significantly influence the result. Currently, the energy generated during the day are assumed to be sent back to grid system and taken back when needed. The fluctuation of energy could affect grid stability; especially the user usage pattern and weather condition various constantly. The weight of each environmental impact shifts along with the climate changes. The decision making might be completely differently later.

Acknowledgement

The house design comes from the HouZe GT team for Race to Zero Competition hold by Department of Energy. We thank our classmates from HouZe GT team who provided data and drawings. Also, we thank Professor John Crittenden for the adivse when we form the paper.

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