# 113: Integration of Architecture and Engineering: A simulation assisted design of zero-energy solar house in the United States

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## Abstract

This paper reports a design and building process of a net-zero-energy modular house, named ElementHouse, which integrated multi-disciplinary knowledge of architecture, mechanical engineering, and electrical engineering. By employing computer-aided simulation tools, several design approaches were developed to achieve the optimal balance among function, aesthetics, economy, and energy. A simplified energy model helped form the building configuration at the preliminary design stage by showing how energy use is affected by various parameters. Energy modelling also estimated the annual energy use and electricity generation, as well as the costs associated with long-term operation. The energy demand estimate and its daily power profile helped design the photovoltaic (PV) system. The modular configuration of the building and its roof structure were then iteratively altered to accommodate the PV panels in such a way as to generate the most power and to facilitate interstate transportation of ElementHouse. Detailed energy simulation using EnergyPlus provided more accurate estimates of power use and generation and, coupled with daylighting simulation performed with Radiance, permitted finalizing the building envelope, opening, and electric lighting design. This paper discusses a way of effectively designing and building a comfortable and affordable solar house.

Keywords: solar house, modularity, net-zero-energy, energy simulation, daylighting, photovoltaic

## 1. ElementHouse and the Solar Decathlon Competition

This paper reports a design and building process of a zero-energy modular house, named ElementHouse, undertaken by interdisciplinary student teams from multiple colleges at the University of Illinois. ElementHouse was entered for the 2007 Solar Decathlon, a competition that takes place in Washington D.C., in the United States, every two years. Twenty teams of university students from the United States, Canada, Germany, Spain, and Puerto Rico competed to "*design, build, and operate the most attractive, effective, and energy-efficient solar-powered house*" [1]. Started in 2002, the Solar Decathlon aims to share new visions for living under the sun: using the newest products and technologies on the market, wasting neither space nor energy, and delivering the promise of a brighter future [1]. The teams transported their solar houses to the competition site (Fig. 1), operated the houses for three weeks, and competed for ten contests, which include Architecture, Engineering, Market Viability, Communications, Comfort Zone, Appliances, Hot Water, Lighting, Energy Balance, and Getting Around.

ElementHouse (Fig. 2), designed and built by students of the University of Illinois at Urbana-Champaign (UIUC), developed a modular system whose application suits various climatic zones. It won two of the ten contests: Market Viability and Comfort Zone. It was also awarded the BP (British Petroleum) Innovation prize for being a solar-run home that catered to the modern needs of a household without interrupting everyday life. ElementHouse addresses the market need for an affordable and practical net-zero-energy home. We employed the conventional building methods and selected green materials that are available and affordable, while developing a modular system that can be flexibly reorganized and expanded. Consequently, each separate module can be manufactured in a mass market and even entirely recycled and independently upgraded.

*Fig 1. The Solar Village on the National Mall, Washington, D.C.*

*Fig 2. ElementHouse designed by University of Illinois at Urbana-Champaign (Credit: Jason Wheeler)*

In this paper, we present ElementHouse from its initial concept to the real construction, which involved multi-disciplinary knowledge of architecture, mechanical engineering, and electrical engineering. We will address the main issues encountered by the ElementHouse student design teams, called *the team* herein, and discuss the corresponding design solutions. Some of the issues were specific to ElementHouse because of the competition rules of the Solar Decathlon, such as height limitation and cross-state transportation; while the other issues universally exist.

Besides applying the new solar technology to the house design, we believe a good cooperation among architects and engineers can encourage new design ideas and achieve energy saving in an economic way. We will focus on the ways of integrating architectural and engineering information at different design stages in order to achieve the optimal balance among function, aesthetics, economy, and energy—a challenge in every solar-powered home integrating passive building design approaches to low energy requirements. We believe the process of solving these problems leads the way to achieving a successful design.

## 2. Initial house configuration and energy simulation

### 2.1 A flexible modular system

The first challenge that the team faced was to find an appropriate form of ElementHouse. On one hand, from an architectural starting point, a Solar Decathlon house needed fast assembly and disassembly and easy transportation because it had to be rebuilt and operated at the competition site. Visual attraction was another focus because the team aimed at designing an aesthetically pleasing house that people would love to live in, instead of solely focused upon solar-powered shelter. On the other hand, an engineering viewpoint favours a building configuration that satisfies the housing function with the least building surface in order to achieve minimum energy losses and gains. How to create interesting interior spaces without sacrificing thermal performance thus became the first problem to be solved for the multi-disciplinary student design teams.

The team came up with the concept of a flexible modular system. The single house, at an interior area of 576 square feet (53.5 m$^2$), consists of three separate modules—or elements, which is why it is called ElementHouse (Fig. 3). The modules are three cuboids of equal size of 12 ft x 16 ft x 11 ft (W x L x H, 3.7 m x 4.9 m x 3.4 m). Each module has independent function of living, kitchen/dining, or sleeping. The unique point of ElementHouse is that the modular system is intentionally expandable and flexibly reorganized, besides the possibility of mass manufacturing. Three basic modules were built for the competition, but the possibilities are almost endless for the number of modules that could be connected to create a larger living space.

*Fig 3. Floor plan of ElementHouse*

An innovative rail system was designed as both temporary foundation and to enable rapid onsite assembly (Fig. 4). The heavy-duty rails, rollers and jacks allowed the house to be constructed assembly line-style and to be moved using simple physics. The first cost of the rail system may increase the initial cost of house construction, but the reusability brings energy saving and environmental protection in a long run.

*Fig 4. A rail system as temporary foundation and assembly line*

### 2.2 Simplified energy simulation

The mechanical engineering team received the basic house configuration and footprint area for energy modelling right after the initial design idea was created. Two approaches were used for simulation: simplified modelling during the initial stage and complex modelling during the intermediate and final stages. The team developed the simplified model using first principles. The complex model was built using a widely used simulation program, EnergyPlus, which is discussed in Section 4 of this paper.

The team decided to develop a custom simplified energy tool capable of studying different concepts in a parametric way while allowing for optimization and economic analyses. The model developed by the team was a steady-state monthly energy analysis based on monthly average weather data with added economic and photovoltaic calculation capabilities. The model did not account for daylighting and thermal mass but it compared reasonably well with results obtained from state-of-the-art models [2]. With knowledge of the area requirements, a simple rectangular area was modelled, and optimization studies for insulation, window area, PV panel area, and orientation were performed. The results were informative to the architectural and electrical engineering teams.

The simplified model also allowed the team to study the effect of insulation thickness on energy use and life cycle cost (LCC), as the insulation is a critical parameter from the engineering and cost points of view. Results showed that by increasing the thickness of the insulation, insulation cost would increase but the energy use would decrease as a result of reduced heating and cooling energy requirements leading to a reduced PV array size and cost. Consequently, an optimal insulation thickness of polyurethane foam, which was chosen for the house due to its better thermal performance than commonly used fibre insulation, was found to be approximately 6 inches (150 mm). Fig. 5 shows the relationship of LCC and the thickness of insulation.

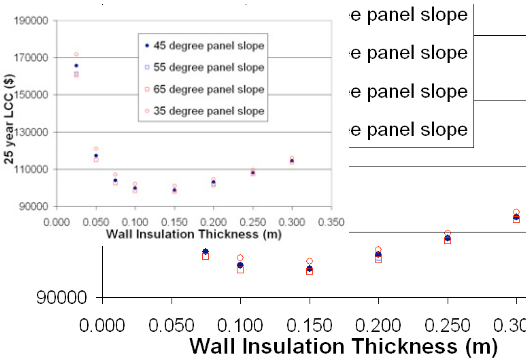

*Fig 5. Optimal insulation thickness obtained during the initial design stage*

In order to be able to flexibly modify the house design and demonstrate high performance with widespread construction techniques, we chose stick-framing structure, 2-by-6 (inch) stud (51 mm x 152 mm) spaced on 24-inch (610-mm) centres, with 4 inches (102 mm) sprayed polyurethane infill for its high insulation value and vapour barrier characteristics. This did not, unfortunately, allow for the optimal insulation thickness discussed above to be achieved. To approach this value as closely as possible, the house was wrapped with a continuous layer of half-inch (13 mm) polyisocyanurate board. Oriented Strand Board (OSB) was attached to both the interior and exterior side of the framing in order to both achieve structural rigidity for transportation and assembly of the house modules and to reduce the framing fraction in the wall. A box-beam construction allowed 3-inch (76-mm) headers above all openings. In addition, the low pitch roof and parapet configuration allowed balloon framing, which kept the top plate from acting as a thermal bridge. Overall, the percentage of wall framing was 13.2%.

## 3. Integration of PV panels

Another challenge to design a solar home is the combination of PV panels with the main body of the house. It is commonly believed that adding solar power to a house is to attach PV panels to the roof. However, a successful design should deem the PV structure as part of the house configuration, rather than leaving it as an aftermarket installation. The team considered the integration of PV panels with ElementHouse at the early stage during the design development. The architectural target was to have the PV structure easily transported, installed, and maintained. The panels should also follow the style of the house and enhance its look. On the other hand, the electrical engineering team was more focused on the power output of the PV panels. The orientation, the angle, and the shadow drawn on the panels all affect the performance of the PV panels. In anticipation of the considerable energy needed to drive an electric car as much as possible for one of the decathlon contests, the electrical engineering team needed to oversize the PV system to supply the house and vehicle needs.

Transportable, optimization for various locations, and good integration with the house while maximizing power output thus became the aim of the team. The basic rule-of-thumb is to have PV arrays facing south (for a house in the northern hemisphere) at tilt angle equal to the latitude of the location of the house. However, for the Solar Decathlon, the house had to be within a solar envelope that was limited to a height of 18 feet (5.5 m). With these goals and limitations in mind, the architectural and the electric engineering design teams worked closely together to design the roof configuration and find the optimal number of PV panels. We simulated expected shadowing and compared several iterations of the PV arrays and house modules positioning on a typical winter morning.

Fig. 6 shows the final roof configuration, which involves the least amount of shadowing throughout the day and year. Additionally, since all the PV panels are at the same angle, the shadowing is cast in a parallel fashion. Electrically, this is less of an issue when it comes to dividing the PV panels into separate arrays, without compromising the total power output; this is explained in Section 5. On the other hand, the PV arrays in roof configuration 4 can be easily folded down within the house module parapets and onto the south exterior walls, facilitating transportation and enhancing the modular aspect of ElementHouse. Finally, PV overhangs on the provided shadings for the south windows, allowing more sunlight to penetrate the house during the winter and less during the summer.

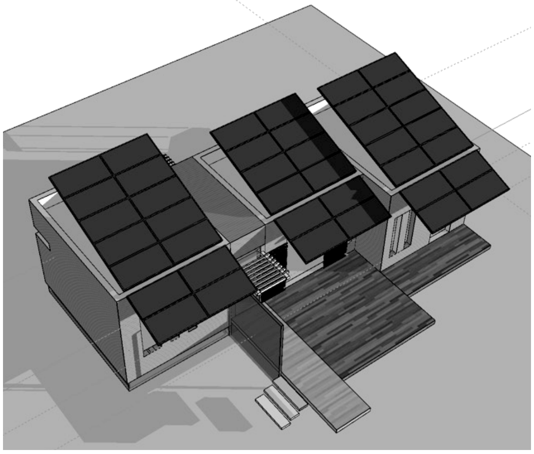

*Fig 6. Final roof configuration*

## 4. Optimization of building openings

### 4.1 Daylighting simulation

The interdisciplinary design approach of the window openings of ElementHouse took into consideration the available daylight and the energy impact. The architectural team wanted to have large window opening to light and visually open the space up. In contrast, the mechanical engineering team suggested smaller windows to reduce the heat loss and gain through the fenestration. The challenge was to design window openings to allow for adequate daylighting and, at the same time, minimize heating and cooling loads. For any amount of window area, the potential savings in lighting loads and associated savings in cooling loads are not large enough to compensate for the increase in heating and cooling loads for this type and size of residential structure. However, windows provide both physiological and psychological benefits beyond daylighting [3].

The team decided to approach the problem from a multidisciplinary perspective. The architectural team created opening designs and studied the quality of daylighting harvest using the specialized lighting software program: Radiance. The simulation team studied those options from the energy standpoint, including energy savings from daylighting using the complex model.

IESNA (Illuminating Engineering Society of North America) lighting standards and suggested luminance level from the 2007 solar decathlon rules and regulations, which suggested minimum 15 to 50 foot-candles (161 to 538 lux) based on different activities, were used as guide for both daylighting and electric lighting simulation. There is not a specified requirement for the daylighting scenario when the lighting levels always tend to be higher than the recommended minimum. In this case, the evenly distribution of daylight is another important gauge to good lighting performance.

Various design approaches of openings were simulated with Radiance throughout simulations for an entire year. The lighting levels on the floors of the house models were compared at noontime with overcast sky conditions. With constant reflectance of the wall, the floor, and the ceiling, 52% 12% and 85% respectively, the sizes and positions of the house openings were varied to test different window to wall ratios, which turned out to be a critical value for the energy simulation. Fig. 7 shows the final configuration of the fenestration.

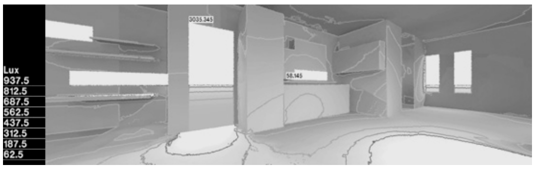

*Fig 7. Illuminance distribution of the final fenestration*

The lesson that the team gained from the daylighting design of ElementHouse was to use the windows wisely. All the windows are designed at various heights and with various shapes for different activities. For instance, the horizontal widow in the kitchen was placed right above the kitchen counter and at eye level height. This location and height provided just the right balance of daylighting and wide view. The size of the window was minimized in such a way without negatively impacting daylight penetration. Openings were placed mainly on the south and north sides of the house with minimum east and west openings. Horizontal windows were placed on the north side of the house to help evenly distribute daylight. Vertical windows on the south side prevented excess solar beam radiation from directly entering the house and provided an excellent method for diffusing the beam radiation throughout the house. They also extended the indoor life out by creating a physical and visual connection with outdoor.

The interaction between engineering and architectural teams yielded several initial design variations for ElementHouse. With EnergyPlus, the team was able to compare how geometric parameters area affected the house performance. Table 1 shows the way the team reduced the surface area and window area gradually until the final design.

Table 1: Geometric parameters for three design stages

| **Parameter** | **Stage 1** | **Stage 2** | **Stage 3** |
|---|---|---|---|
| Total Wall Area ($m^2$) | 179.04 | 115.21 | 110.87 |
| Roof Area ($m^2$) | 51.95 | 52.67 | 52.65 |
| Floor Area ($m^2$) | 51.95 | 52.67 | 52.65 |
| Heat Transfer Area ($m^2$) | 207.43 | 203.8 | 199.46 |
| Window Area ($m^2$) | 23.56 | 16.75 | 16.71 |

Energy simulation also helped decide window construction. Multiple window constructions were modelled and quadruple pane windows were found to be ideal for competition purposes because of their notable increase in thermal insulation and resulting decrease in heating and cooling requirements.

### 4.1 Electric lighting and control

The selection and design of the electrical lighting system was coupled with the opening design. The team considered dimmable fluorescent lighting systems to provide additional lighting only when daylighting was incapable of providing all lighting required. Florescent lights were amounted on the ceiling with indirect light fixture along the perimeter of each module. They were grouped independently in the three house modules and respectively controlled by three daylight sensors. Lights within each module were further divided into subgroup based on their distance to the windows, which enhanced the even lighting distribution and saved energy in the mean time.

In addition to numerical simulation, laboratory experiments with various lighting systems were conducted in order to determine the most appropriate option for the lighting need. Light emitting diode(LED), compact fluorescent, and incandescent were tested in similar settings. It was concluded that LEDs would provide desired levels required for task lighting applications with minimum power.

## 5. Electric System

Fig. 8 shows the topology of the stand-alone PV electrical system used by ElementHouse. The topology is governed by the number of PV panels, the ratings of the PV panel, and the ratings of the other electrical components. To obtain the maximum power out of these PV panels, the team carefully chose one of the most efficient multi-crystalline PV panels on the market. The final roof configuration in Section 3 can accommodate forty such PV panels. Each of the forty panels has an efficiency of about 15% and is rated at 185 watts (W), totalling to a system of 7400 W.

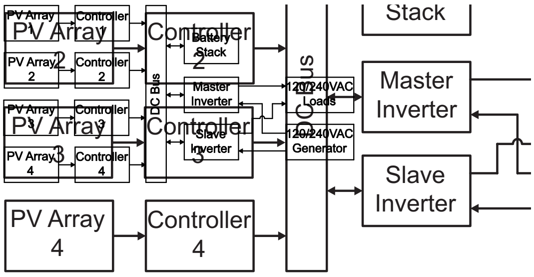

*Fig 8. Stand-alone PV electrical system*

The forty PV panels had to be divided into four separate arrays of ten PV panels—five parallel strings of two serial panels—to comply with the input voltage and current ratings of the controller unit. Note that the PV panels, which were shown to be shadowed in the morning in Section 3, were grouped in one array so that shadowing never affected the other arrays. The controller unit is a combination of a maximum power point tracking (MPPT) device and a charge controller. The MPPT device maintains the operation of each PV array at its maximum power point (MPP) [4], while the charge controller ensures the proper charging of the battery stack.

The battery stack is equivalent to an energy storage capacity of 41 kilowatt-hours (kWh)—enough to power ElementHouse for more than a day in the absence of solar energy.

## 6. Mechanical system

In accordance with the modularity concept pursued throughout the design of ElementHouse, custom mini-split heat pumps were installed in each module of the building. The heat pumps were designed and built by the team. The interior heat exchangers of the mini-split heat pump systems were composed of a drop ceiling of wire-on-tube heat exchangers of the type used in static domestic refrigeration condensers. The heat exchangers used radiation and natural convection to provide sensible heating or cooling to the space. Whether they provided heating or cooling depended on the setting of the valves of the heat pumps.

An off-the-shelf dehumidifier handled latent loads. By separating the sensible and latent load conditioning, the team acquired increased flexibility and better comfort conditioning control. Ventilation air was provided with a separate whole-house heat recovery ventilator (HRV) system. During the competition, the team did not use the HRV and instead relied on natural ventilation by opening doors.

For water heating, during the initial stage of simulation through the simplified model, an economic comparison was conducted between using a PV powered heat pump water heater and using solar thermal technology. It is widely accepted that solar thermal is a highly feasible option for water heating in solar homes. However, for this application, the use of a heat pump system could provide some benefits including the simplicity of using a single solar array, eliminating additional piping, and the flexibility of hot water supply.

The final design was modelled for three locations with different climatic conditions: Springfield (Illinois), Sterling (Virginia), and Phoenix (Arizona). The house was able to keep energy balance although PV electricity generation and heating/cooling loads obviously change between these locations. Figs. 9 and 10 show the simulation result of Springfield (42.12° latitude and -72.62° longitude). As noted in Fig. 9, the PV design accounted for a significant portion of the energy being used for the electric car, which was part of the competition.

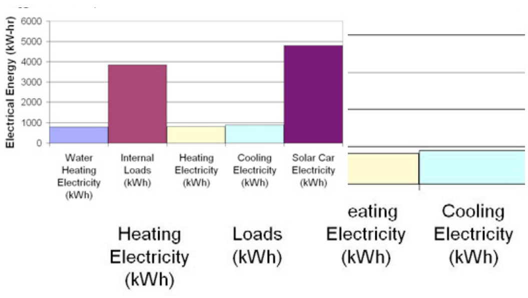

*Fig 9. Breakdown of Annual Electrical Energy requirements for Springfield, Illinois*

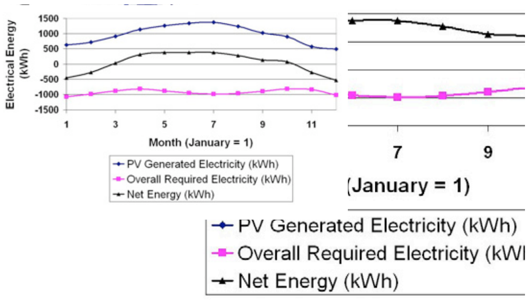

*Fig 10. Annual Energy Balance Springfield, Illinois*

## 7. Achievement of expected building performance and discussion

Excellent cooperation between engineering and architecture at different design stages is the key for delivering a comfortable and energy-efficient solar house. The team was awarded first prize in the Market Viability contest. ElementHouse drew considerable public attention to net-zero-energy houses. One valuable lesson the team gained was how to use indoor space smartly and identify all the design details which would optimize energy saving. The performance of the comfort conditioning system during the Solar Decathlon was excellent allowing the house to also be awarded first prize in the Comfort Zone contest.

Other competitors lacked the ability to separately control temperature and humidity. They had difficulty in simultaneously controlling temperature and humidity and had to accept either one or both being out of range. This is likely due to attempts to condition control by dry bulb temperature and with relatively low sensible loads, failing to keep the system long enough to dehumidify. The ability to control temperature and humidity separately allowed the ElementHouse team to have greater flexibility in maintaining the required latent and sensible conditions.

The overall dc power balance (Fig. 11) shows the performance of the house and its PV electrical system. The energy balance was negative by the end of the competition week due to the cloudy weather on the last two days of the competition week, as shown by the decreasing solar radiation in Fig. 11. Note that, even though the first three days of the competition week were sunny, the solar radiation never got close to a clear sky reading of 1 kW/m$^2$, further impeding the PV arrays from outputting their maximum power. Furthermore, if the competition were to continue for another week, the energy balance would have easily become positive again. The generally agreed upon goal of a net-zero-energy house is to have zero or positive energy balance over the course of a year.

In short, the University of Illinois student teams sought to prove that addressing the visual and aesthetic does not mean sacrificing price, marketability, and performance. The team designed and built a house which demonstrated that solar power is a reliable and affordable energy source when well integrated into the design of a home. By competing in the 2007 Solar Decathlon, the team achieved its goals to demonstrate to a wide public audience that a solar home can be comfortable, serving many choices of daily activities, as it is also an energy-efficient and environmentally friendly home. The team also met the great challenge of delivering an affordable and marketable home.

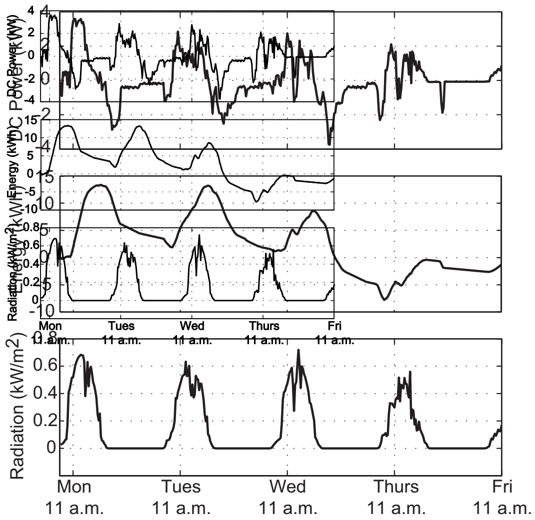

*Fig 11. Overall dc power, energy balance, and solar radiation during the decathlon week*

## 6. Acknowledgements

We would like to express our gratitude to all the students who helped design, build, and transport ElementHouse. We want to thank the University of Illinois at Urbana-Champaign for giving us financial support. We are deeply indebted to our faculty advisors, Prof. Ty Newell, Prof. Michael McCulley, and Prof. Patrick Chapman, who guided and encouraged us all the time.

## 7. References

1. 2007 Solar Decathlon, [Online], Available:http://www.solardecathlon.org[16 June 2008].

2. Martinez, L. A., (2007). Simulation of Solar Decathlon House. Master’s Thesis, University of Illinois at Urbana-Champaign.

3. Leslie, R.P., (2002). Capturing the daylight dividend in buildings: Why and how? *Building and Environment*, 38 (2): p. 381-5.

4. Esram, T. and P. L.Chapman, (2007). Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Transactions on Energy Conversion*, 22(2): p. 439-48.