NET-ZERO HOUSES: DESIGNING FOR THE 2013 SOLAR DECATHLON

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ABSTRACT

Residential buildings contribute a significant percentage of total energy consumption in developed countries and about eleven percent in the USA. Among U.S. governmental initiatives related to solar energy application to residential design, the Solar Decathlon competition, organized by the U.S. Department of Energy, stands out as the most architecturally relevant.
Through the lens of a 2013 Solar Decathlon entry, this paper discusses the evolution of technologies and the changes in the architecture of the American single-family house when solar energy is used as a primary energy source. The design strategy of our 2013 Solar Decathlon team is to maximize the effectiveness of the PV array while keeping the costs low. The resulting net-zero house will also be significantly more affordable than the typical Solar Decathlon house, which is a fundamental condition if these houses are to have an impact in the housing market.

Keywords: Solar Decathlon, Solar houses, Net-zero houses, North American house

1. INTRODUCTION: FORM FOLLOWS PERFORMANCE

Building technology and environmental problems have been driving forces in shaping modern architecture worldwide. For over thirty years, technical experimentation and innovation in housing and house design have focused on decreasing the household energy consumption[1]. The relatively low cost of energy in the US has not encouraged major changes in house types and construction systems over the last few decades. However government programs[2] in conjunction with an increased public awareness of energy and environmental problems have encouraged a gradual evolution of the housing market, lowering the energy use for appliances, increasing the efficiency of HVAC systems, and improving the thermal performance of the housing envelope.

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Designers and builders have made many attempts during this time to introduce the use of solar energy into residential building design, in the form of passive systems, active hot water panels for space or domestic hot water heating, or PV panels for electricity production, with varying degrees of market success[3]. The growing pressures to reduce fossil fuel consumption and the uncertainties of nuclear power have contributed to a growth (Fig. 1) of photovoltaic (PV) system use in the U.S.[4].
The Solar Decathlon competition, sponsored by the U.S. Department of Energy, has addressed the issue of solar house design, construction and performance since 2002. Its relevance for this paper lies in the importance that this competition places on the combination of engineering innovation and architectural appeal. The homes created for this competition must be an integrated package that can be realistically marketed to the American public. This paper uses the Solar Decathlon as a vehicle to discuss the question of how the house typology and architectural vocabulary are affected by solar energy considerations. This question must be addressed in order to devise ways to integrate these design requirements into houses that can be realistically produced for the private market. The question is, therefore: how does the integration of solar energy systems impact the design of the American home? Are dramatic changes necessary, which may affect house form and even the layout of neighborhoods, or can technologies such as PV (with related energy-saving technologies) be integrated into the house types typically expected in the American market?

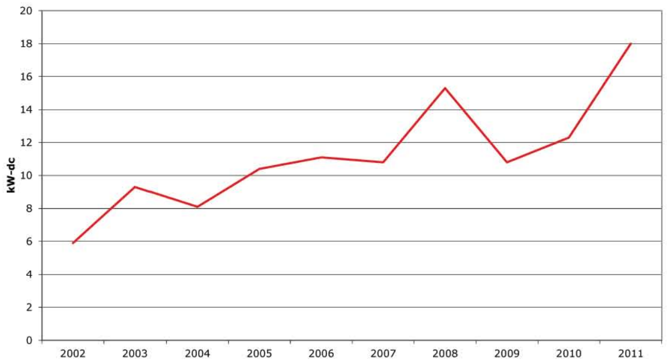

Figure 1. Average Capacity of Distributed Photovoltaic Installations (2002-2011). (*From IREC, Solar Market Trend Report 2011*)

Both approaches have to address the thermal efficiency of the building envelope and follow some basic rules for effective use of solar panels and solar energy in general. When using either design approach it is important to understand how solar energy is collected and used. The solar energy systems and the interaction of these systems with the rest of the building systems, especially the building envelope, will affect the architecture and the cost of the house. Establishing clear rules or guidelines that can be used by builders and designers can contribute to improved efficiency of the housing stock and to an increased use of solar energy with consequent reduction of fossil fuel consumption.

Figure 2. Purdue University 2011 Solar Decathlon house. Computer-generated rendering. *(Courtesy of the Purdue University Solar Decathlon team)*

In addition to guiding development of basic design criteria, the design question is relevant in relation to architectural theory. In this regard, it asks if, or to what extent, architectural design is driven by technologies, and more specifically what is the impact of a 21st century resource-conservation design focus. Will a house become an energy system supported by a dwelling, or a dwelling supported by an energy system? If we accept that resource conservation is a socio-cultural choice driven by economy and politics, then the resulting house typologies will consequently reflect the characteristics of a region or a country (its climate, materials, culture, energy constraints and opportunities, etc.). In this sense we can establish the characteristics of true regionalisms and even define the character of a national residential architecture[6].

2. AMERICAN SOLAR HOUSES AND ENERGY POLICY

Do solar houses look different from other houses? What do we mean by "solar house?" The simplest and most obvious features can be observed in modern solar house prototypes such as the 1939 MIT solar house using flat plate solar collectors, and a second MIT prototype (Fig. 3) built in 1959. The 1959 MIT home used the principles established by Keck and Keck in their 1940 Glenview, Illinois, "first American solar house," [7] and featured a south-facing greenhouse space that was capable of producing hot air on a sunny winter day. The technical design complexity with this type of solution relates to the ability of the system to circulate the warm air to the rest of the house and retain the heat so that the temperature would remain comfortable during the night. This requires good insulation and some thermal storage.

These prototypes represent a solar energy design approach called solar-mechanical, where some energy is used to circulate hot water or warm air, in combination with passive solar solutions (thermal storage in floor structures or walls, direct space heating through windows, natural ventilation and natural convection). The house has to have a long side facing south to support these types of heating systems, and there is a strong architectural difference in house form using roof solar collectors versus sunrooms. Sunrooms can be attached to the south side of the house, as in the

Glenview house, or dominate the entire house form, as in the Solar IV house. Many houses of this type were built in the 1960s and 1970s with a vertical sunroom forming an atrium in the center of the house, a solution used for the Living Environments Concept House built by General Electric (GE) in Massachusetts in 1989 as a laboratory (the primary goal was actually to test and showcase plastic products ranging from pipes to structural panels).

Figure 3. MIT Solar IV house, Lexington, Mass. (From *MIT Solar 7,* Massachusetts Institute of Technology)

Twenty years later GE went further with it Net Zero Energy Home Project (Fig. 4), featuring photovoltaic panels[8]. This project, started in 2009, aims at commercializing integrated home energy-saving systems by 2015. The systems include a 3kW to 4kW PV array and a small wind turbine on the roof, a Home Energy Manager monitoring energy consumption, a smart meter, a geothermal heat pump for heating and cooling, a heat pump water heater, and energy-efficient lighting. According to GE, a net-zero energy home would cost about 10 percent more by 2015. As discussed later, the cost today is still much higher than that.

Both active solar collectors and passive sunrooms have remained a rarity in the US housing market, due to the additional construction costs that cannot be recovered rapidly with savings in energy. Natural gas remains the most prevalent fuel for heating homes in the United States. Over 55 million homes (49 percent) use natural gas as the main fuel source for space heating. Electricity as the main heating source increased from 29 percent of homes in 2005 to 34 percent in 2009 while the use of fuel oil as the main heating source continued to decline. In 1993, more than 10 percent of homes were heated with fuel oil, but by 2009 this had declined to about six percent[9].

Figure 4. Net Zero Energy Home Project, 2009, General Electric (*Courtesy of General Electric*)

Another significant problem is that while solar passive systems can be effective in regions where the primary energy demand is for winter heating, they do not help in the many areas with hot and humid climates where there is a significant need for summer cooling. These areas, ranging from Texas up to the northern USA, represent a large percentage of the U.S. population. The solar energy solution in this case is to produce electricity with PV panels in order to power an air conditioning system. Modern PV arrays that can fit on the roof of a single-family house can supply much, in some cases all, of the energy demand of an American household.

How this can be accomplished is best illustrated by the houses built for the 2011 Solar Decathlon, which are required to have a net-zero energy balance, i.e. the output from the PV system must equal or exceed the total house energy consumption. Because residential energy demand is not synchronous with supply from a PV system (which varies depending on the season as well as the time of day), the system must be supported with storage batteries and/or connected to the grid via an appropriate meter. This allows the house to sell electricity to the grid when the PV output outstrips the demand, and vice versa.

3. THE ARCHITECTURE OF SOLAR DECATHLON HOUSES

The Solar Decathlon is a biannual competition for solar-powered homes sponsored by the U.S. Department of Energy (USDOE). The first Solar Decathlon was held in 2002 with fourteen teams (all from the U.S.). Subsequent competitions were held in 2005, 2007, 2009 and 2011. The first five competitions were conducted on the National Mall in Washington, DC.

Team Kentuckiana will be competing in the 2013 Solar Decathlon competition along with nineteen other teams—sixteen of the teams are from the US, two are from Canada, and two from Europe. The 2013 competition will be held at Orange

County Great Park in Irvine, CA. Entrants are selected by the USDOE following a competitive proposal process.
The Solar Decathlon is named for the ten contests that constitute the competition. Several of the contests (such as Architecture) are juried; and several (such as Energy Balance) are measured. The nature of the contests and the criteria for success have changed somewhat during the history of the Solar Decathlon.
Reducing the Solar Decathlon to its essence, a successful entry will demonstrate net-zero energy performance during the ten days of the active competition, will be architecturally appealing, will be judged appropriate for its defined target demographic, will not exceed a fixed construction budget, will comply with USDOE rules and regulations, and will do well in specific areas such as lighting, thermal comfort and hot water production. Each of the ten contests is worth 100 points, for a total of 1000 points. The design, construction and operational challenge for participating teams is to not fail in any contest, do pretty well in most contests, and excel in a few contests. This is a serious challenge for student-led teams—which is definitely a big part of the ongoing allure of the Solar Decathlon.
There are many aspects that go into the design, construction and operation of a high-performance building. Typically, if a project claims "greenness," it will exceed (often substantially) the prevailing minimum code requirements for energy efficiency and water efficiency; provide better-than-normal interior conditions; and use materials that are environmentally preferable. The Solar Decathlon competition does not demand green projects. It does, however, emphatically demand high-performance in the realm of energy. As stated on the Solar Decathlon web site:

> *"The U.S. Department of Energy Solar Decathlon challenges collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive. The winner of the competition is the team that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency."*

The objective of optimal energy production and maximum efficiency is reiterated in the criteria for the Energy Balance contest of the competition:

> *"In the Energy Balance Contest, a team receives full points for producing at least as much energy as its house needs, thus achieving a net energy consumption of zero during contest week. This is accomplished by balancing production and consumption."*

The Solar Decathlon energy performance expectations hinge on a project that can function with net-zero energy for the duration of the competition in Irvine, California—and ideally on an annual basis on its home turf. As defined by the National Renewable Energy Laboratory (NREL) a [site] net-zero energy building "produces at least as much energy as it uses in a year, when accounted for at the site." It is also possible to define net-zero energy on the basis of source energy or energy costs.
The Solar Decathlon, like most current high-performance building projects, sets site energy as the target to be mitigated by on-site (solar) energy production. Equilibrium between energy used and energy produced is established by net metering during the Solar Decathlon competition. From a design perspective, the less energy-efficient a net-zero building the larger the required solar components—

and vice versa. Since solar components (solar thermal, PV) are typically more expensive than efficient systems, net-zero energy buildings usually aggressively push the envelope on the demand side of the supply/demand equation.

Studies conducted during the Solar Decathlon design process provide some answers to the question of how house architecture is affected by a net-zero energy objective. These houses typically use an array of roof-mounted PV panels to produce sufficient electricity to run a 1000 ft^2 (93 m^2) single-family house. We will call these systems solar-electric (able to produce electricity), to distinguish them from solar thermal (active or passive systems directly producing heat).

Clearly the design issues that have an impact on architectural language and house form are orientation, window location and size; shading devices, roof form (if using solar panels); and envelope integrity. Another order of consideration is the increased attention to internal loads, such as lighting and appliances.

The roof form is one of the first impacts of PV technology on architectural appearance. Due to transportation constraints related to the Solar Decathlon competition, an efficient solution is to have prefabricated housing modules with flat roofs, on which the PV arrays can be mounted on site. In the 2011 competition more than half of the houses had a flat roof, four had PVs on a low-pitch roof (below 15°) (Fig. 5) and the remaining four (such as the Purdue University house) had a steeper, more conventional North American pitch roof system. All houses avoided vertical PVs, such as the wall- mounted system adopted by Team Germany in 2009, due to the inefficiency and resulting cost impact of this configuration.

Figure 5. Computer-generated rendering of the Team Maryland house, an example of a low-pitch roof with PV panels. This house won first prize in the 2011 Solar Decathlon. *(Courtesy of the University of Maryland Solar Decathlon team)*

Optimal annual PV production will typically result from an array tilted to the site latitude—an engineering solution that may not mesh with architectural intentions.

Accepting reduced PV output to accommodate an architecturally preferred roof pitch is a common compromise.The integration of PV arrays with roof design depends first of all on the area of PV modules necessary to power the house. The PV array/floor area ratio is typically (and currently, with 14% efficiency PVs) around 0.77 for the highly-energy-efficient houses designed for the competition, meaning that a 1,000 ft^2 (93 m^2) single story house may require about 770 ft^2 (72 m^2) of PV, including the mounting and spacing of PV panels forming an array[10]. This ratio would of course change depending on the envelope thermal performance, climate and energy efficiency of the building systems and appliances, as well as on the ratio of the enclosed volume to envelope area. Furthermore, as the PV panel efficiency increases, a smaller roof area is required to provide the same kWh output. Some of the energy demand, for instance hot water, can also be offset by other systems, such as solar thermal and heat recovery devices, decreasing the area of the PV array.

4. THE DESIGN STRATEGY

The Team Kentuckiana prototype addresses the problem of post-disaster reconstruction, with a durable, permanent house that can be delivered and site-assembled very quickly. In this design scenario, natural disasters often damage infrastructure so severely that the ability to produce electricity with PV panels allows a replacement home to be placed quickly and operate for some time independently from the grid. Once the grid has been restored, the PV powered homes can serve as a distributed green power generator, increasing the power capacity of the community.

One design strategy to balance energy demand with production is to lower energy demand as far as possible. This is the strategy that the Passivhaus design approach takes[11]. In this approach, the heating demand of the home is reduced to the point where a traditional heating system is no longer required. Cooling demand may be reduced by ventilation and night cooling. This approach requires very efficient exterior envelopes, very efficient building systems, and generally requires significant changes in traditional architectural choices to ensure this energy demand is low enough.

An alternative design strategy is to maximize the efficiency of the PV array and of the house envelope, while keeping cost low with a balance of low cost arrays, reasonable levels of demand control, and avoiding the very expensive, high-efficiency technical solutions. This is the approach that Team Kentuckiana has taken in its design efforts for the 2013 Solar Decathlon.

Climatic conditions in Kentucky and southern Indiana require both heating and cooling. To support the high electricity loads demanded by active climate control, a PV array of about 650 ft^2 (about 60 m^2) on a roof pitch close to 30° is planned. This is a good tilt for the PV panels, since the latitude of Louisville, Kentucky (the heart of the design-focus region) is 38°. Figure 6 shows a design solution investigated for the Team Kentuckiana house. Although lower roof pitches could be accommodated, especially with angled PV arrays, rows of PV panels installed at steeper angles would have to be spaced to avoid overshadowing, making this solution less effective compared to a 30° roof. Furthermore, placing the panels directly on the roof reduces the connection costs for the arrays. During the preliminary design of the Team Kentuckiana house, a series of whole building energy analyses were conducted.

Figure 6. An early version of the Team Kentuckiana house, showing the integration of the PV array on the south-facing roof

In these analyses varying amounts of thermal insulation were used in the building envelope and the effects of these variations on yearly energy use were investigated. Fig. 7 shows the effect of increasing thermal resistance on annual energy use in Louisville, Kentucky. It can be seen from this figure that there is a steep reduction in energy use for increasing thermal resistance, up to a point. After this point, further increases in R-value have much less of an effect on annual energy use. Fig. 8 shows the yearly energy savings as a function of R for each condition. This analysis was then used to set design R values of 30 for the floor (raised above ground), 30 for the walls, and 60 for the roof/ceiling. It was not automatically assumed that super-insulated walls and roofs were needed to produce an energy-efficient design, and in fact little energy savings could be realized for higher insulation values.

A similar analysis was conducted to investigate the type and placement of windows in the building design. This analysis verified that larger windows with significant shading and low solar heat gain coefficients should be used on the southern exposures and windows should be limited on the north, east, and west faces. It was also determined that multi-paned, gas-filled window systems did not provide much better energy performance than a reasonably efficient double pane systems. Window size and location had a much bigger effect than performance characteristics.

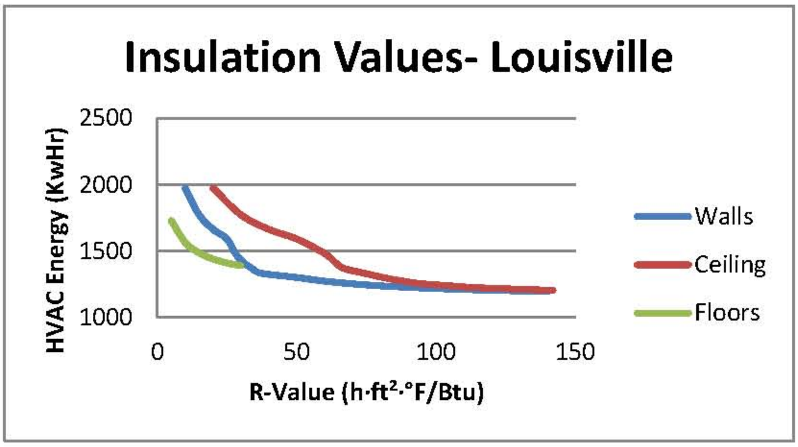

Figure 7. Total annual energy consumption vs. R-value in Louisville, KY

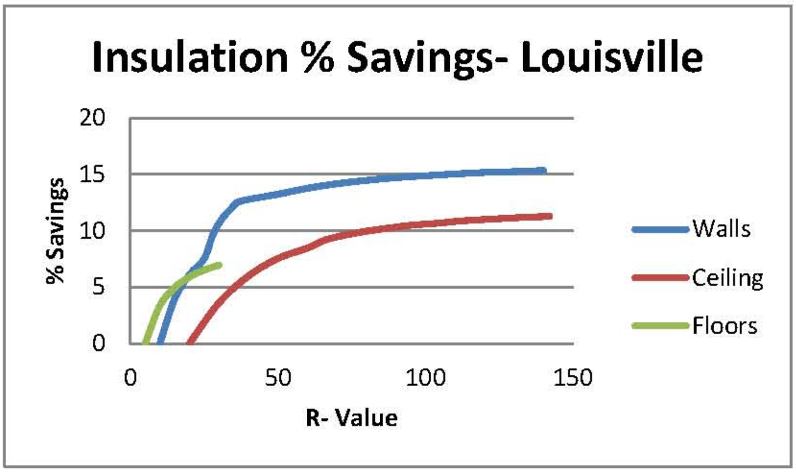

Figure 8. Percent annual energy savings vs. R-value in Louisville, KY

The design solution was informed by these analyses and incorporates passive heating and cooling strategies through the use of moderately high insulation values with an effective house form and careful window placement and sizing. The windows were also oriented to allow good cross ventilation. Natural ventilation will be most thermally effective in the early summer and fall months. This requires that the house plan extend east-west for the maximum permissible length. This orientation also makes this house type practical in typical urban neighborhoods, characterized by narrow E-W lots with streets on the east or west side. A variety of scenarios of post-disaster reconstruction of neighborhoods have been studied to evaluate the solar access conditions of a variety of housing layouts, as shown in Fig. 9.

Figure 9. An urban design study testing the density of housing development with roof-mounted PV arrays. The density can be considerably higher than the solution shown

5. CONCLUSIONS: THE FUTURE OF SOLAR-ELECTRIC HOUSES

One of the goals of the Solar Decathlon competition is to produce cost-effective net-zero energy homes. The cost of net-zero energy houses, as demonstrated in the 2011 Solar Decathlon, is still much higher than the cost of an ordinary house. With a target Solar Decathlon cost of \$ 250,000 and a nominal floor area of 1000 ft^2 (93 m^2) these net-zero houses (without site acquisition) cost around \$ 250 per ft^2 (\$ 2,688 per m^2)—compared to a national average cost of \$ 80 per ft^2 (\$ 860 per m^2)[12]. Since the 1970s, significant changes have already taken place in engineering American homes for improved energy efficiency, including advanced framing, new insulating systems such as structural insulated panels, and automated controls (from the 1989 Smart House to the 2009 GE Net Zero House). However, at the same time, residential "plug loads" have increased dramatically with the number and complexity of domestic appliances. In addition, the average house size has also increased. However, even with these inflationary influences, residential energy consumption has still been declining. Furthermore, heating systems increasingly use electricity-driven heat pumps, suggesting that more homes will be using only electrical energy sources, shifting the heating energy sources away from direct combustion.

From an environmental point of view, even the Solar Decathlon net-zero houses are far from ensuring zero-carbon emissions, particularly when transportation and land development are included. These houses may represent an intermediate step if energy costs were to escalate, while PV systems become cheaper and electric cars more common. In addition to the "smart grid," microgrids could also contribute to efficiencies and economies of house construction and energy distribution. This suggests that major changes could be driven not by the house becoming autonomous from the grid but instead more dependent on a compact infrastructure, with utilities shifting part of the energy production from large centralized plants to small local PV systems, perhaps integrated into commercial as well as residential buildings.

The Solar Decathlon houses may fail to provide a truly holistic solution, but are nevertheless a very useful experiment in the development of design methods and strategies that future generations of architects can apply to a variety of energy efficient building designs. The integrated design experience also allows both engineers and designers to more accurately assess how early design choices can impact the energy performance of a building. Rules of thumb often encourage, erroneously, the belief that "if a little is good a lot is much better." Being competitive in the Solar Decathlon completion demands the skillful integration of engineering and architectural solutions, something that is still woefully lacking in most building projects.

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