Quantifying Sustainable Improvements: Interactions of Energy Efficient Construction Techniques and Estimating Their Efficiency

Kyle Pustola, and Dr. Can B. Aktas, *University of New Haven*

***Abstract*—Many sustainable building improvements can be implemented in order to increase a building's efficiency. The article demonstrates ways in which improvements can be tested, compared, and evaluated together to identify synergies among different improvements to find the best return on investment by quantifying potential savings both in electricity and energy consumption of buildings. The goal of the study was to assess the possibility and ease of determining economic savings from energy improvements installed in a building design project. With the tools and methods discussed in the study, reasonable estimates for savings can be made quickly and efficiently for people looking to invest in improvements for their homes or buildings, allowing them to calculate payback periods with confidence and help them get the most out of their investment decisions.**

***Index Terms*—building energy analysis, Climate Consultant, energy efficiency, HEED, passive design**

I. Introduction

The built environment frequently receives the utmost attention in environmental impact reduction efforts, as buildings are responsible for a significant share of energy consumption in most countries. New technological advances on multiple fronts have made the idea of living in a zero emission and zero net energy home a reality [1]. However, the sheer number of solutions and design strategies now available present new problems related to the selection of solutions to be applied to a specific circumstance for the most cost effective result. The intent of this study was to gain a better understanding of which design solutions work best for a building model in the New Haven, Connecticut region, to determine if and how such strategies interact, and quantify economic savings and payback periods by implementing those strategies. To this end, multiple tools available to designers were explored, and a few selected to carry out the intended research. As for scope, the study focuses on electric use and heating, ventilation, and air conditioning (HVAC) energy use for buildings.

Manuscript received February 5, 2014.

K. Pustola is an undergraduate student with the Mechanical, Civil, and Environmental Engineering Department, University of New Haven, West Haven, CT 06516 USA (phone: 203-232-2764; fax: 203-720-2816; e-mail: kylepustola@gmail.com)

II. Background

A. Building Energy Efficiency

Energy efficiency measures ranging from the product level scaled up to entire buildings are receiving due attention as nations aim to improve their environmental performance while at the same time improving economic performance by spending less on building utilities. However, a strong knowledge base and easy to use tools for designers and professionals are still catching up with recent developments. A case study from the Swiss residential sector identified incomplete knowledge on pricing, benefits, and availability of new technologies as barriers to making sound investment decision-making with regards to energy efficiency measures [2]. Many countries now have codes that require a certain level of building energy efficiency. However, strict adherence to such codes alone may not be the most cost-effective way to improve building efficiency, as such policies may not capture the full benefits of synergies or new technologies [3].

The most vital utilities a building requires for human occupation and comfort are electricity, water, and heat. Regarding electricity use, environmental impact analysis is relatively straightforward; a product or technology that consumes less electricity during use, or one that generates additional electricity on-site from renewable sources should be preferred over others. The analysis would consist of how much electricity is consumed versus how much is produced, with the goal being to have the difference be zero or a net gain in electricity produced over a period of time.

The analysis of energy used to maintain the buildings comfort level is more complicated. First, while a pattern of demand for electricity can be estimated over a period of time, based on people in the building, time of day, etc., the weather outside is always changing. Temperature, humidity, cloud cover, hours of daylight, strength of solar radiation, and many other variables affect outdoor conditions, while the indoor condition must be maintained within acceptable limits set by occupants; commonly around 70-75°F and 50-80% relative humidity.

C. B. Aktas is an Assistant Professor with the Mechanical, Civil, and Environmental Engineering Department, University of New Haven, West Haven, CT 06516 USA (e-mail: caktas@newhaven.edu)

978-1-4799-5233-5/14/$31.00 ©2014 IEEE

Second, there are a wide variety of active and passive design methods and techniques that can be used to make the indoor environment comfortable for occupants. The layout of windows, type of walls and roof, the thickness of the walls and roof, fans and airflow in and through the building, even the orientation of the building can affect HVAC performance and energy efficiency. Designing buildings in isolation from its surroundings and climatic conditions may result in poor energy performance in the final product. However, without a viable, easy to use, customizable tool that can measure the effectiveness of individual and all strategies, practitioners may fail to take advantage of location and design specific opportunities that may arise.

Several computer programs have been developed over the years to aid designers faced with the challenging task of analyzing and designing for building efficiency. Builderguide, Energy-10, COMcheck, HEED, EnergyPlus, and Climate Consultant are some of the tools that may be used for this purpose. The current study used HEED version 4.0 and Climate Consultant to quantify economic savings of energy efficiency measures.

B. *Thermal Interactions in Buildings*

To better understand the various interactions that go into making the indoor environment comfortable, some mathematical relationships used to describe heat transfer should be examined.

The thermal conductivity of a building's walls, roof, and floor, affect how quickly the outdoor temperature can have an effect on the indoor temperature. In building construction, the thermal conductivity is described as an R-value [4]. The lower the thermal resistance, the higher the rate of heat transfer, and the less effective the material is as an insulator. Using outdoor climatic conditions and type of material used in construction, one can calculate how much heat is lost (or gained) by an indoor space over a period of time. The effect of the sun on the building is an important factor that must be taken into account, as areas that receive sunlight will have a higher temperature than areas in shade, which affect the temperature differential between the interior and exterior surfaces of the building envelope. This is only a first step in predicting the interior environment of a building. Another consideration would be outside wind speed, which causes convection, and can speed up the heat transfer from the exterior surface of the building. Additionally, thermal mass effect must be taken into account, along with humidity, airflow, and two and three dimensional heat transfer. All of these equations must be used with constantly varying outdoor conditions. These considerations only scratch the surface of the heat transfer mechanics going on while an HVAC system works to maintain a constant, comfortable environment for indoor occupants.

The average designer or building professional may not be highly knowledgeable in thermodynamic relationships to the extent needed to properly implement all of the calculations required to analyze building efficiency and comfort. Hence, the importance of practical computer tools that can simulate and analyze a given specific condition are highlighted.

III. Engineering Education

Although most of the efficiency technologies described in this paper have existed for some time, the industry has had trouble applying them to everyday projects, besides doing so only to meet advancing code requirements. If clients and builders had reasonable estimates for future cash savings and payback periods, they may be more inclined to include these technologies into their proposals. An additional educational focus on these passive and sustainable technologies, along with guidelines and techniques for applying and analyzing them, should be applied to the education of engineers.

Adding this facet to the education of engineers is essential to be competitive in the still-emerging market of sustainable design and construction. Because of the interactions of the building system, the scope of this education must include electrical, mechanical, civil engineers, and architects as well. If a building is being designed and only one branch of the design team is educated in these sustainable technologies (for example, the mechanical engineer), then the passive gains from building orientation, window placement, eve placement, etc., will not be realized and therefore the building will not be as efficient as it could be. This holistic approach to building design requires the cooperation and education of all of the building design and construction trades.

IV. Methods

The two primary tools used in the study were Climate Consultant and HEED v4.0. Climate Consultant uses Environment & Public Works (EPW) format climate data gathered from thousands of weather stations around the world to graphically display information about temperature, wind speed and direction, humidity, cloud cover, solar radiation, daylight hours, and even underground temperature [5]. It allows the user to enter data about the acceptable comfort range for their indoor environment and provides a psychrometric chart describing and ranking various techniques to most effectively maintain the desired comfort level, which defaults to the California Energy Code Model. The comfort level for this test was left at the default settings, but this could be modified by the user in order to optimize efficiency of the heating and cooling system, as well as to match other regional energy codes or to meet specific design requirements. The case study was carried out for a building in New Haven, CT. For this analysis, after reviewing several other locations, climate data from Tweed Airport in New Haven, CT was used mainly due to its proximity. The selection provided complete and exhaustive data for HVAC calculations, as it provided all of the variables for the exterior condition in an easy to understand package. An additional benefit of using Climate Consultant was the ability to export data directly into HEED, version 4.0 used in the study.

The other tool used extensively for the project was HEED: Home Energy Efficient Design. The main purpose of the tool is to design, analyze, and compare different methods for conserving energy in buildings. HEED defaults to the 2008 California energy code for references. The program uses comprehensive EPW climate data to model the exterior conditions, and uses user input to determine the wall and roof type and layout, insulation, window type and layout, floor plan, building orientation, level of air infiltration, ventilation systems, electrical use, and even photovoltaic (PV) panels and solar hot water systems. The user can customize up to nine different scenarios (designated as "schemes" by HEED) and compare one against the other. Using HEED and climate data from the EPW website, nine different scenarios were defined to assess how incremental changes in building design influenced its energy performance. These specifications of these nine scenarios are described below. Performance was ranked in monetary terms, by the total dollar amount of energy used in a year. The building size chosen for the study was a 2016 ft^2 2-story building, having a building footprint of 36 ft by 28 ft.

CASE 1 (Baseline):

- R values: walls = 11, ceiling = 19, and floor = 11 (Older energy code, default option)
- The wide face of the building orientated east (no consideration for solar gain)
- Windows are spread out equally on each side of the building.
- Glass: Clear double pane in wood or vinyl frame (U = .51, SHGC (Solar Heat Gain Coefficient) =.52, Tvis (Visible Transmittance) = .57)
- No full-house ventilation system
- Infiltration: Ducted HVAC System without special duct sealing (4.3 SLA, Specific Leakage Area)
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 2:

- R values: walls = 11, ceiling = 19, and floor = 11
- Wide face of the building is orientated south for maximum solar gain
- Window layout changed so most windows face south.
- Glass is clear double pane in wood or vinyl frame (U = .51, SHGC =.52, Tvis = .57)
- Eves added to south facing windows (3.21' deep eves, offset 1' to each side of window)
- No full-house ventilation system
- Infiltration: Ducted HVAC System without special duct sealing (4.3 SLA)
- Furnace: 78% AFUE
- Air Conditioner: 13.0 SEER

CASE 3: (Default Setting: Meets California Energy Code)

- R Values: walls = 21, roof = 38, floor = 19 (Default for "Meets Current Energy Code")
- Wide face of the building is orientated south for maximum solar gain
- Window layout changed so most windows face south.
- Window type: energy code minimum for climate zone 16 (U = .40, SHGC = .5, Tvis = .63)
- No full-house ventilation system
- Infiltration: Ducted HVAC system w/ sealed ducts (3.8 SLA)
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 4:

- R Values: walls = 31, roof = 57, floor = 28 (1.5 * Energy Code, default selection option)
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Glass is clear double pane in wood or vinyl frame (U = .51, SHGC =.52, Tvis = .57)
- Eves on south facing windows (3.21' deep eves, offset 1' to each side of window)
- Infiltration: Air-retarding house wrap, all joints lapped and tapped (3.3 SLA)
- No full-house ventilation system, but windows are manually opened if cooling is needed and outdoor temperature is below comfort high
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 5: (Preferred energy use under 2008 California Energy Code, Default selection option)

- R Values: walls = 21, roof = 38, floor = 19
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Windows are low E double pane glass (U = .40, SHGC = .40, Tvis = .63)
- Eves on south facing windows (3.21' deep eves, offset 1' to each side of window)
- Full-house ventilation system installed. Interior air velocity at 300 fpm, small whole house fan w/ 5 air changes / hour, smart thermostat controlled exhaust fan.
- Infiltration: Ducted HVAC system w/ sealed ducts (3.8 SLA)
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 6:

- R Values: walls = 42, roof = 76, floor = 38 (2 * Energy Code, default selection option)
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Windows are low E double pane glass (U = .40, SHGC = .40, Tvis = .63)
- Eves on south facing windows (3.21' deep eves, offset 1' to

each side of window)
- No full-house ventilation system, but windows are manually opened if cooling is needed and outdoor temperature is below comfort high
- Infiltration: Air-Retarding house wrap, all joints lapped and tapped (3.3 SLA)
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 7:
- R Values: walls = 31, roof = 57, floor = 28
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Glass: Clear double pane in wood or vinyl frame (U = .51, SHGC =.52, Tvis = .57)
- Eves: South facing windows (3.21' deep eves, offset 1' to each side of window)
- Full-house ventilation system installed. Interior air velocity at 300 fpm, large whole house fan w/ 20 air changes / hour, smart thermostat controlled exhaust fan.
- Infiltration: Air-Retarding house wrap, all joints lapped and tapped (3.3 SLA)
- Furnace: 78% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: 13.0 SEER(Seasonal Energy Efficiency Ratio)

CASE 8:
- R Values: walls = 42, roof = 76, floor = 38
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Glass: Clear Argon filled double pane low-E squared wood/vinyl (U = .36, SHGC = .28, Tvis = .64)
- Eves: South facing windows (3.21' deep eves, offset 1' to each side of window)
- Trees added around north, east, and west faces of house for shading and wind barrier
- Operable Shading: Exterior light-colored slatted blinds automated hourly
- Full-house ventilation system installed. Interior air velocity at 300 fpm, large whole house fan w/ 20 air changes / hour, smart thermostat controlled exhaust fan. Windows are manually opened if cooling is needed and outdoor temperature is below comfort high
- Infiltration: Sealed building (1.5 SLA)
- Furnace: 78% AFUE
- Air Conditioner: 13.0 SEER
- PV System: 14 Scheuten Solar USA P6-60U-210W panels with Ablerex Electronics ES 3300-US-240 inverter.
- Solar hot water system: 2 panels, Alternate Energy Technologies AE-21 panels, 2 50 gallon storage tanks, 135□F minimum solar tank temperature

CASE 9:
- R Values: walls = 42, roof = 76, floor = 38
- Wide face of the building is orientated south for maximum solar gain
- Window layout: most windows face south.
- Glass: Clear Argon filled double pane low-E squared wood/vinyl (U = .36, SHGC = .28, Tvis = .64)
- Eves: South facing windows (3.21' deep eves, offset 1' to each side of window)
- Operable Shading: Exterior light-colored slatted blinds automated hourly
- Full-house ventilation system installed. Interior air velocity at 300 fpm, large whole house fan w/ 20 air changes / hour, smart thermostat controlled exhaust fan. Windows are manually opened if cooling is needed and outdoor temperature is below comfort high
- Infiltration: Sealed building (1.5 SLA)
- Furnace: Condensation furnace, 97% AFUE (Annual fuel utilization efficiency)
- Air Conditioner: Split system, 19.0 SEER (Seasonal Energy Efficiency Ratio)
- PV System: 14 Scheuten Solar USA P6-60U-210W panels with Ablerex Electronics ES 3300-US-240 inverter.
- Solar hot water system: 2 panels, Alternate Energy Technologies AE-21 panels, 2 50 gallon storage tanks, 135□F minimum solar tank temperature

The software also provides visual representations of applied design features described above. Two such representations have been presented in Fig. 1, for Cases 2 and 8 respectively.

V. Results and Discussion

Results show that the most effective way to reduce energy consumption was to use PV and solar hot water, as seen by a 36% reduction in energy consumption between Cases 7 and 8. The next most effective way would be to increase the exterior insulation of the building by doubling the value required by the California Energy Code, where a 30% reduction was observed switching from Case 2 to Case 6. The third most effective option was found to be a combination of installing a full-house ventilation system and increasing the efficiency of windows by using low E double pane glass, where an 18% reduction was calculated switching from Case 3 to Case 5. Table I presents economic analysis results of the nine scenarios examined in this study together with potential savings compared to the baseline scenario. Fig. 2 displays the breakdown of electricity and heating energy costs after applying energy efficiency measures described in each Case. Given the will to invest in energy efficiency combined with the knowledge of how to achieve project goals, results show that existing technologies can be used to significantly reduce the energy consumption of buildings by employing several effective strategies. Fig. 3 presents an example for air conditioning power demand on a daily and monthly basis, by taking into account the energy efficiency contribution of modeled strategies. However, these results are based on the specific building tested within the study at a certain location, and should not necessarily be generalized to other locations and building designs without repeating a similar analysis.

With the use of such tools, informed decisions can be made at the consumer level or even at policy-making level, where individual homeowners or entire cities can best assess the effectiveness of certain technologies specific to their climatic conditions, therefore increasing the feasibility and effectiveness of energy efficiency projects in general.

TABLE I
Economic Analysis Results for Cases Considered

Case or Scheme	Cost/year ($)	Savings compared to baseline (%)
CASE 1: Baseline	2,580	-
CASE 2: Orientation and window eves	2,350	9
CASE 3: Meets Energy Code (Default setting)	2,100	19
CASE 4: Increase Insulation to (1.5 * energy code)	1,660	36
CASE 5: Ideal efficiency (Default setting)	1,640	37
CASE 6: Increase Insulation to (2 * Energy code)	1,590	39
CASE 7: Additional Ventilation	1,580	39
CASE 8: PV & SHW	648	75
CASE 9: Install high efficiency HVAC system	524	80

A limitation that was noticed in HEED was the lack of an option for adding custom materials with known specifications, which would greatly increase the capabilities of the user in a design and analysis program such as this. Such a function would enable the tool to be used for even more applications.

VI. Conclusions

The goal of the study was to assess the possibility and ease of determining economic savings from energy improvements installed in a building design project. With the tools and methods discussed in the study, reasonable estimates for savings can be made quickly and efficiently for people looking to invest in improvements for their homes or buildings, allowing them to calculate payback periods with confidence and help them get the most out of their investments. These programs enable quantification and comparison of different designs, and offer the client reasonable estimates of efficiency savings in each case. Overall, the tools and strategies discussed herein are an invaluable step towards designing efficient building systems as localized and individualized building designs can be tested for indoor climatic conditions and energy efficiency, in response to external climatic conditions.

References

[1] D. D. Chiras, The Solar House: Passive Heating and Cooling. White River Junction, VT: Chelsea Green Pub., 2002.

[2] M. Jakob, "Marginal costs and co-benefits of energy efficiency investments: The case of the Swiss residential sector," Energy Policy, vol. 34, no. 2, pp. 172-187, Jan. 2006.

[3] J. Morrissey, and R. E. Horne, "Life cycle cost implications of energy efficiency measures in new residential buildings," Energy and Buildings, vol. 43, no. 4, pp. 915-924, Apr. 2011.

[4] Y. A. Çengel, J. M. Cimbala, and R. H. Turner, Fundamentals of Thermal-fluid Sciences. New York: McGraw-Hill, 2012.

[5] M. Murray. (2013, December). *Energy Design Tools* [Online]. Available: http://www.energy-design-tools.aud.ucla.edu

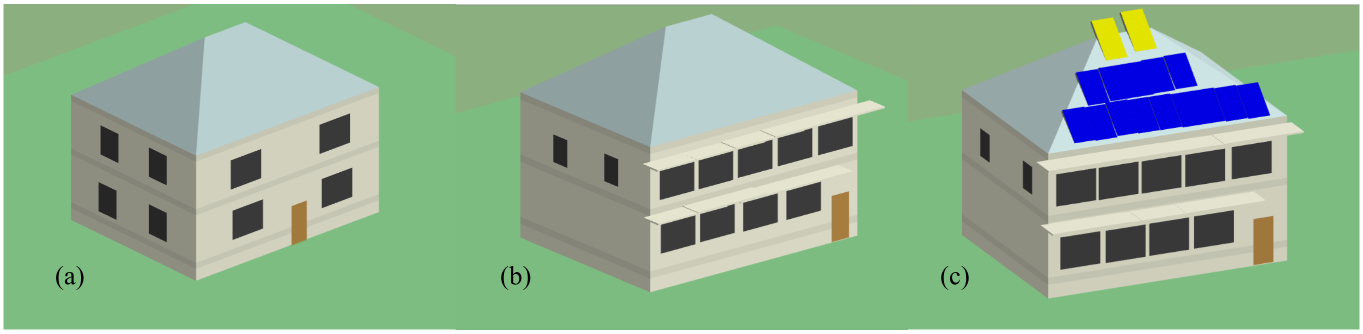

Fig. 1. A visual representation of energy efficiency design measures employed and tested by different scenarios. (a) Baseline window and door layout, east facing side (b) Case 2 with window and door layout reconfigured to face south, with protruding eaves on top of windows (c) South facing side of Case 8 showing PV and solar hot water panels applied to the south facing side only of building roof

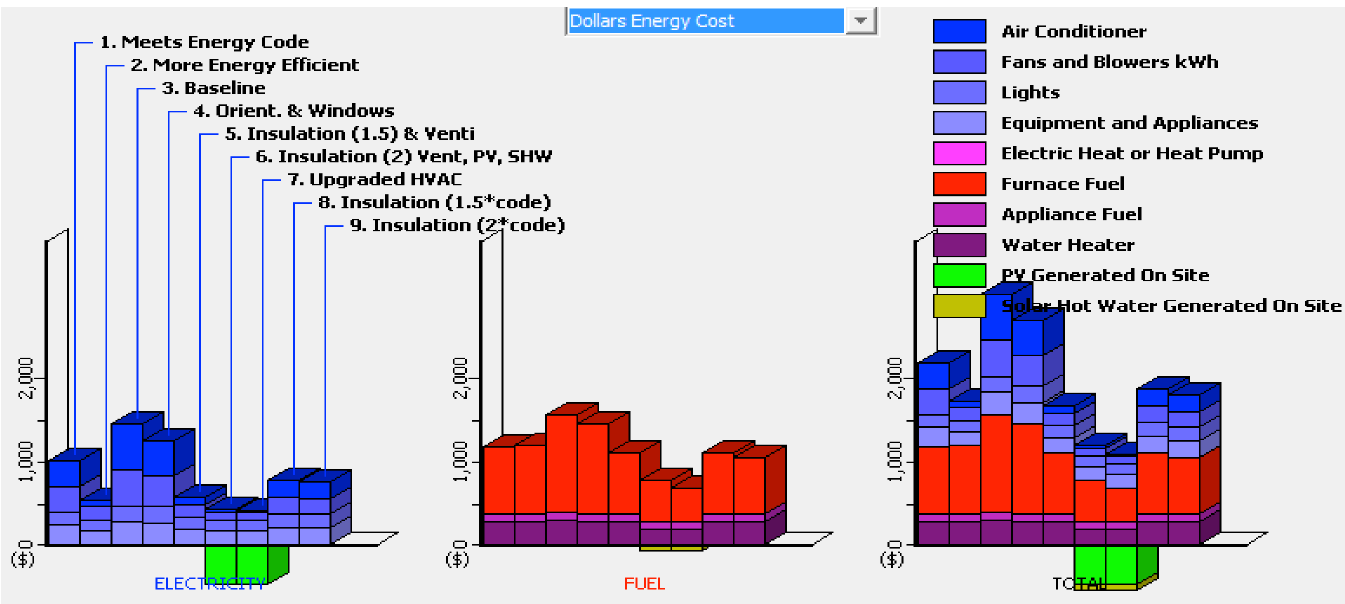

Fig. 2. Graphical display for energy cost of nine cases considered in the study, with electricity and fuel cost shown separately as well as together for total cost

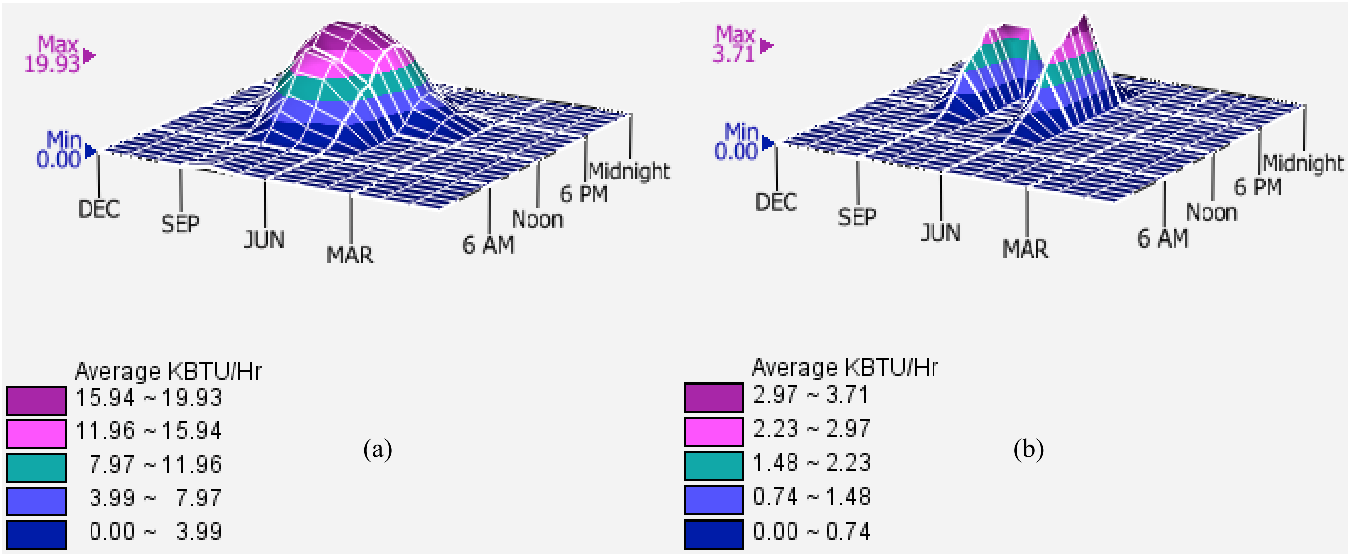

Fig. 3. HEED results displayed in a 3-D graph displaying months of a year, hours of a day, and the power demand of the air conditioner system between a comparison among two Cases (Case 1 and Case 9). Note the changes in maximum output and curvature due to introduction of window eves, automated shades acting during the warmest summer months, combined with an increase in insulation.