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Comprehensive energy and economic analyses on a zero energy house versus a conventional house

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ABSTRACT

A zero energy house (ZEH) was built side by side with a baseline house in suburban Las Vegas. Actual energy performance measurements were carried out on the incorporated energy saving features and solar applications. The data show that a radiant barrier and a water-cooled air conditioner are major contributors to the energy savings, while an insulated floor slab and thermal mass walls are not effective for energy-conservation during cooling periods. Photovoltaic roof tiles produce enough green power to cover the use in the ZEH, and the solar water heater can reach a peak efficiency of 80%. The energy saving contribution of each incorporated component was obtained using Energy10 and eQUEST3.6 models, and then these codes were used for economic application evaluation. The two analysis codes yield similar results that compare well with the actual building performance data. Four items are clearly economically valuable for these applications: high performance windows, compact fluorescent lights, highly-insulated roofs and air conditioners with water-cooled condensers. PV tiles show a good financial return when rebates are considered. The Integrated Collector Storage (ICS) unit has a high efficiency but with a little higher thermal price. Thermal mass walls are too costly to have wide market appeal.

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1. Introduction

Energy usage in the building sector is increasing rapidly, and there is the necessity to reduce fossil fuel consumption. Fossil fuel usage for building applications results in the dwindling of energy resources and deteriorating of environmental conditions. Two approaches can be used to mitigate these two effects: enhancing the energy saving features of buildings and using renewable energy sources like solar, wind and biomass. When a building is supplied enough electricity from renewables, it can perform as a zero energy house (ZEH), usually defined as such on an annual basis. Great impetus has been provided by governments around the world through financial support programs. Many low energy consumption buildings and even ZEHs have been constructed and determined to be effective marketing approaches.

An old building has been retrofitted for lower energy consumption in Tianjin China, using energy saving aspects and the so-called radiant panel technology renewable system developed by Tianjin University [1,2]. It has been shown that the heating/cooling energy usage was cut by 92%. The International Energy Agency (IEA) tasks result in 12 advanced solar low energy houses which show an energy saving of 60% compared with typical houses [3]. An early overview of solar system design was given by Kreith and Kreider in 1976, which emphasized the design of collector systems for space heating and cooling [4]. A 15-yr research program at Princeton University was reviewed which featured field measurements of the energy performance of buildings, which show the actually energy savings achieved [5]. The energy-conservation potential for five district-heated buildings of three types in southwest Sweden is analyzed and the percentage lies between 30 and 60% of final energy use [6]. The energy-conservation potential for space and water heating was calculated to be 35–40% of the final energy use for a Swedish district-heating system in buildings [7]. School buildings (238 in total) in Hellas were audited and the annual average total energy consumption was found to be 93 kWh/m^2 [8]. The energy use in a typical commercial building in Hong Kong was monitored and simulated with TRACE 600, and the energy saving performance was compared with similar buildings [9].

By using thermal insulation the electricity consumption due to the building envelope and carbon dioxide emissions are anticipated to be reduced 40% in Bahrain [10]. Modern energy efficient technologies are desperately needed in Malaysia, and a comprehensive survey was performed to show the feasibility of adopting new

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programs in different sectors [11]. By using solar control films together with daylight-linked lighting controls in subtropical Hong Kong, electric lighting of a fully air-conditioned open-plan office was cut down 21.2% and cooling energy consumption was decreased by 6.9% [12]. Experimental work and mathematical evaluation showed that a significant reduction of the whole building cooling load in the range of 6–49% was found after a green roof system was installed on a nursery school building in Athens [13]. Boonekamp [14] in the Netherlands developed a framework that can deal with the interactive effects among various energy saving measures, which provides a basis for energy policy settings. A fully decentralized system was used on an office building in Tokyo, and the comparative results show that the new system can have a potential CO_2 reduction of over 30% at an estimated capital increase of about 70% [15]. By applying roof coatings that have high reflectivity (about 72%), energy saving performance of a small non-residential building was tested in comparison to the conventional one that has a roof reflectivity of about 26% [16]. The TRNSYS code was used to simulate the energy performance of modern houses in Cyprus. It is found that roof insulation is the most important factor that influences the space heating and cooling load [17].

In America many programs have been carried out and have produced significant numbers of demonstration buildings [18,19]. Nearly two million green housing units are being built every year in the US, yielding more environmentally friendly structures and comfortable indoor conditions [20].

In suburban Las Vegas, two identical floor plan homes have been built side by side: one using conventional methods meeting the minimum required building code. A companion one was constructed with the same floor plan but incorporating innovative new technologies including energy saving features and solar applications. Real-time data acquisition has been carried out for nearly three years and valuable performance information has been determined. Detailed analyses can be made on almost any building component using actual data. Since there are so many items included in the building that all interact, simulation models that have been validated by comparing with real usage in the two houses have been used to investigate the contributions of individual items when performing as a group.

2. Energy saving approaches in the ZEH

The ZEH is a modified version of the baseline. The houses have the same but mirrored floor plan and the same living area of 151.2 m^2. The roof assembly of the ZEH was rotated from east–west to north–south for a favorable solar orientation for the PV system. The ZEH has many energy saving features, including an insulated slab, high R-value attic, high performance windows, massive exterior walls, water-cooled AC and on-demand gas heater. In addition solar applications of roof-mounted PV tiles and domestic water preheater were adopted. Further descriptions are given below.

3. Measurements in the ZEH

To monitor the temperature as well as heat transmission in the ZEH a wide array of thermocouples and heat flux sensors have been installed at a variety of wall locations. Fast response thermocouples with self-adhesive backing (SA1-J-72, 30AWG wire, 72″ leads, Omega Company) and thin film transducer HFS-4 ($1.18'' \times 1.38''$, Sensitivity: 6.5 μV/Btu/ft^{2}hr, Omega Company) were embedded in the plaster layer of the interior surfaces of exterior walls. Thermocouple temperature sensors with Perfluoroalkoxy (PFA) Teflon insulation (5TC-TT-J-20-72, 20 AWG, 72″ leads, Omega Company) were embedded in the stucco layer of the exterior surfaces of the exterior walls. Floor temperatures were measured at locations near the south wall, in the middle of the floor plan, and near the north wall. These temperatures were measured at a depth of 12.7 mm. Outside temperature at floor level was also measured. The temperature sensors used are all Type-J thermocouples of 5TC-TT-J-20-72. The same type of temperature sensor was used to detect the indoor air temperature. HFS-4 thin film heat flux sensors were installed at the bottom surface of the ceiling to measure the transient heat transmission from the ceiling to the house. For the integrated collector storage (ICS) solar water heater, thermocouples of TC-J-NPT-G-72 (fiberglass insulation, 20 AWG wire, 72″ leads, Omega Company) were used to measure the inlet and outlet water temperatures.

The energy consumption monitored in the houses was categorized into electricity, natural gas, and water. Detailed electrical consumption monitoring is performed primarily with Watt-hour meters (Wattnode, CCS) that were installed at the main breaker panel in the garage. Water consumption is monitored using a variety of flow meters. A turbine water meter of FTB-4107A-P (Omega Company) was used for the ICS unit. A low flow impeller water meter (SPX-038, Seametrics Company) was installed for the FREUS evaporative condenser. Natural gas consumption is monitored using typical gas meters. The whole house gas consumption is measured by a gas meter with pulse encoder of Pulsepoint which was manufactured by Riotronics Company.

A weather station also mounted on the roof of the ZEH records the ambient temperature, relative humidity, incoming solar radiation, and wind conditions. The outdoor ambient air temperature and relative humidity probe is type HMP50-L40 and provided by Vaisala Company. Incoming solar radiation is measured by a CS-LI200X pyranometer, and the wind conditions are measured by a CS-03001 Wind Sentry. The Wind Sentry includes a CS-03101-5 anemometer and a CS-3301-5 vane which records wind speed and direction, respectively.

Wires connecting each sensor were run through the attic to the garage where the data-logger is mounted. The data-logger is a CS-CR10X measurement and control module that is connected to a CS-AM 16/32 multiplexer and a CS-SDM-SW8A pulse counter. Signals from both houses are recorded by the CS-AM 16/32 Relay Multiplexer with an interval of 1 min. A 9600-baud CS-COM210 telephone modem connected to the CS-CR10X via serial I/O port allows the data to be accessed remotely by a computer and downloaded for analysis.

4. Performance analyses based on actual data

4.1. Insulated slab

With 102 mm extruded polystyrene (XPS) board vertical insulation, the *F*-factor for slab-on-grade floors is lowered from 0.73 in the baseline house to 0.58 in the ZEH. *F*-factor is the heat loss of below-grade foundations and is in terms of linear feet of perimeter. This number gives the heat loss for a slab per lineal foot of perimeter, and an *F*-factor is multiplied by a perimeter length and degree-days to obtain the total heat loss. So, correspondingly, the overall heat loss rate is decreased from 73.2 W/K for a perimeter of 57.9 m to 58.1 W/K. The temperature distribution and variation in both houses are shown in Fig. 1.

It is shown in Fig. 1a that the point temperature near the centerline of the house has the least variation because it is farthest away from the outside climate effects and is significantly influenced by the inside temperature. Because the location of this temperature is least affected by the solar irradiation, the north floor temperature is closest to the outside ground temperature. In comparison, the south floor area has a higher temperature in heating seasons caused by the heat transferred through the

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