THE DEVELOPMENT OF IMPROVED ENERGY EFFICIENT HOUSING FOR THAILAND UTILIZING RENEWABLE ENERGY TECHNOLOGY

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ABSTRACT

The paper reports on the results of research to reduce energy consumption in residential buildings in a hot and humid climate region (Thailand) using efficient architectural building components, energy efficient building systems, and renewable energy systems (solar energy) to produce electricity and heat domestic hot water. The solar energy system used in the analysis of the supplemental energy was a hybrid photovoltaic-thermal (PV-T^2) collector system, which is a combination photovoltaic (for producing electricity) and solar thermal collector (for producing hot water), and night-time radiator for radiating unwanted heat to the night sky. The research methods used in this work included instrumentation of a case study house, experimental data collected from an experimental PV-T^2 collector system (Rasisuttha 2004), and calibrated building thermal simulation using DOE-2 (LBNL, 1982; 2000).

INTRODUCTION

The world's primary energy sources rely heavily on fossil fuels such as oil, natural gas and coal. Unfortunately, combustion of fossil fuels releases carbon dioxide (CO_2) and other greenhouse gases, as well as pollutants that have contributed to environmental problems such as global warming, air and water pollution, and other damage to the earth's ecosystems. Furthermore, as the world's population and energy consumption continue to increase, environmental problems will continue to worsen unless more efficient, affordable buildings can be built that utilize a higher proportion of renewable energy.

In 2001, the world's energy consumption was 404 quadrillion Btu (1 Quad = 1 x 10^{15} Btu) and is projected to increase by 58 percent to 640 Quads from 2001 to 2025 (i.e., 1.9 percent average annual growth) according to the Energy Information Administration (EIA, 2003). In developing countries, which include Asia, the Middle East, Africa, and Central and South America, energy consumption was 139 Quads in 2001 and is expected to increase by 94 percent to 270 Quads over the same period (i.e., a 2.8 percent average annual growth) (EIA, 2003). Thus, by 2025, the energy use in the developing countries will constitute about 42 percent of the total global energy consumption.

Interestingly, during the period from 1997 to 1998, Thailand's energy consumption decreased at the rate of 8.9 percent due to the Asia's economic recession. In 1998, Thailand's total energy consumption was 1.83 Quads, which was consumed by four sectors: transportation – 41.3 percent, industrial – 32.2 percent, residential and commercial – 22.4 percent, and other – 4.1 percent (DEDP, 1998). In spite of the total decrease, energy consumption in the residential and commercial sector increased by 1.6 percent in 1997, while there were drastic reductions in other sectors (DEDP, 1998). Furthermore, electric demand in the residential sector increased by 17 percent from 1996 to 1998 (DEDP, 1998). After Asia's economic crisis, the Thai economy recovered and energy consumption dramatically increased. In 2002, Thailand's total energy consumption was 2.2 Quads (a 20 percent increased from 1.83 Quads in 1998), a relatively high average annual growth rate of 6 percent comparing to 3.2 percent, the long-term (2002 to 2025) average annual growth of energy consumption by developing countries in Asia forecasted by the EIA. Finally, Thailand's total electricity consumption increased by 24 percent from 1998 to 2002 (from 79,899 GWh to 99,122 GWh).

Unfortunately, over 80 percent of Thailand's energy comes from non-renewable energy (DEDP, 1998). Furthermore, since Thailand depends on imported energy, which constitutes about 43.4 percent of the total energy consumption, Thailand's energy supply is very dependent on world energy market fluctuations, which can cause havoc with Thailand's economy.

In 1996, there were 15 million private households according to National Statistical Office (NSO, 1996); of those, 12 million or 80 percent were single-family detached houses, which comprised about 50 percent of the total residential energy use. The remaining 20 percent of the dwellings (3 million dwellings), which are row houses and apartments, consumed as much energy as the detached housing. The typical Thai residential construction is concrete post and beam construction, which has been adopted because of severe termite infestation and limited supplies of wood. In residential construction, concrete is not only used to support building structures, it is also used for brick mortar (i.e., cement) and whitewash stucco finishing of the brick and concrete block walls. Concrete and brick are high thermal mass materials, but have low thermal resistance (R-Value) (approximately 2.0 and 3.3 $h \cdot ft^2 \cdot F/Btu$, respectively) (TGP, 1996). These material properties allow heat to be stored in the building envelope, where it can be released during evening hours when ambient temperatures decrease. Unfortunately, the typical construction materials for Thai houses are non-insulative, and construction techniques need to be improved.

Using renewable energy as an energy source is an option to reduce the consumption of non-renewable energy. In residential buildings, solar energy has been utilized for space heating, and domestic hot water, and for generating electricity using photovoltaic (PV) solar systems. Such systems would seem to be ideal for Thailand since Thailand is located near the equator and has high levels of sunshine year-round. Bangkok's monthly average daily radiation on a horizontal surface varies little from January to December (ranging from 16 to 20 MJ/m^2) (Duffie and Beckman, 1991). Thus, solar energy could be an abundant source of energy for Thailand.

Since more than 40 percent of Thailand's energy is imported, and with the awareness of environmental problems, the Thai government has been promoting the use of PV through research funds and through demonstrations of PV systems in residential buildings. Although PV is still new in Thailand's housing industry, with the government's new policy, the potential for PV systems to become an essential key to reducing energy use in Thai residential buildings is promising.

One photovoltaic system, the hybrid photovoltaic-thermal (PV-T) collector system, has been investigated by several researchers over the last 20 years (Rockendorf et al., 1999). The hybrid photovoltaic-thermal (PV-T) collector system is a combination photovoltaic (for producing electricity) and solar thermal collector (for producing hot water) system. Studies of this collector have highlighted the advantages of the hybrid PV-T collector system over separate systems of PV and solar thermal collectors in terms of system efficiency and economics. Unfortunately, very little experimental data exists that demonstrates the advantages of a combined system. Therefore, one of the objectives of this study was to conduct an experimental study of this system as an auxiliary energy source for Thai residential building. Furthermore, no previous studies could be found that inventigated a hybrid photovoltaic-thermal ($PV\text{-}T^2$) that is a combination photovoltaic (for producing electricity), solar thermal collector (for producing hot water), and nighttime radiator (for radiating stored heat to the sky at night). Hence, this paper reports selected results from the development and testing of such a $PV\text{-}T^2$ system (Rasisuttha 2004).

TASKS

The tasks for this study are listed as the following (Rasisuttha 2004).

1. Identify and characterize energy use of a case-study house in a hot-humid climate, Thailand.
2. Identify energy efficient residential design features for typical houses in a hot-humid climate using a calibrated simulation.
3. Develop and test a hybrid Photovoltaic-Thermal ($PV\text{-}T^2$) system.
4. Apply the test results of the hybrid $PV\text{-}T^2$ system to the case-study house.
5. Develop generalized design and housing characteristics in terms of energy conservation and affordability, which are appropriate for hot-humid climates.

METHODOLOGY

The research methods used in this work include instrumenting a case study house, and an experimental $PV\text{-}T^2$ collector system, along with building thermal simulation. The required data and information were in three categories: the building, the building's energy use, and climate. A typical contemporary Thai detached house was selected as a case study as shown in Figure 1. Building data include the building description, types and properties of the materials, and construction. The monthly utility bills of the case study house were also collected and used for comparison with the simulated energy use.

The required weather data was categorized in two levels: macroclimate and microclimate. Bangkok weather data was acquired as a macroclimate data, which included air temperature, relative humidity, solar radiation, and wind speed. Microclimate data were obtained by field measurements of indoor conditions at the case study site during a 7 month period (June to December, 2000). Measurement devices (portable data loggers) for measuring and recording temperature and humidity were calibrated and then installed in the case study building, including: the conditioned spaces, unconditioned spaces, and the attic.

Figure 1: The Case-study House.

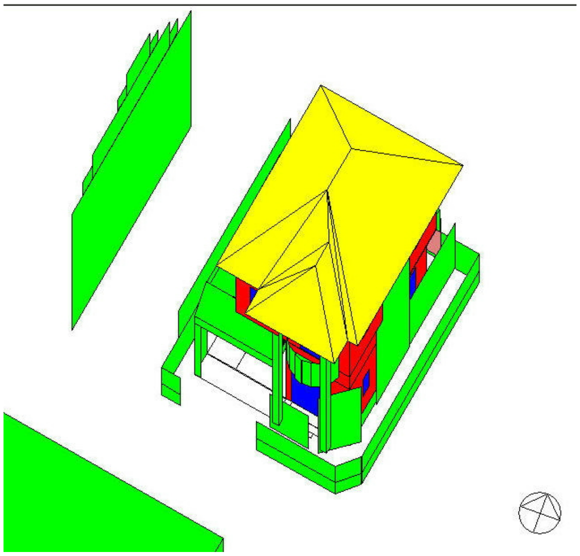


Figure 2: Architectural Rendering of the Base-Case House.

The building geometrical data were obtained from the architectural drawings, and confirmed with site inspections. A computer model of the case study building was constructed using the DOE-2 program (LBNL 1982; 2000). An architectural rendering program (Huang, 1994), was used to check the accuracy of the geometrical data in the DOE-2 model which is shown in Figure 2. A simulated model was developed as a base case, which represented the case study building in terms of thermal conditions and energy consumption. The base-case model then was improved by simulating the reduced energy use of a number of energy efficient design strategies:

Strategy 1-1: R-7 fiberglass insulation installed on the underside of the roof tiles.

Strategy 1-2: R-14 fiberglass insulation installed on the underside of the roof tiles.

Strategy 2: Increase heat resistance of insulation placed on the 2nd floor ceiling (upgraded from existing R-11 to R-28 fiberglass insulation).

Strategy 3: Use of light-weight concrete block walls.

Strategy 3-1: 4”(10 cm) light-weight concrete block.

Strategy 3-2: 6”(15 cm) light-weight concrete block.

Strategy 3-3: 4” light-weight concrete block with insulation on the outside wall.

Strategy 3-4: 4” light-weight concrete block with insulation on the inside wall.

Strategy 4: Replace single-pane clear glass with double- pane low-e glazing (tinted).

Strategy 5: Install shading devices (vertical and horizontal fins) for windows on south, east and west.

Strategy 6: use high thermal mass walls (increase mass of existing wall (4” brick).

Strategy 6-1: 8”(20 cm) brick wall.

Strategy 6-2: 12”(30 cm) brick wall.

Strategy 7: Use SEER-12 air-conditioning systems (upgraded from the existing SEER 10 air-conditioners).

Strategy 8: Use electronic ballasts: replace magnetic ballasts of 32W, T-9 circline lamps with electronic ballasts.

Strategy 9: Replace existing refrigerators with energy efficient refrigerators.

Strategy 10: Generate on-site supplemental thermal (DHW) and electricity. Both supplemental energies produced by a hybrid PV-T^2 collector system (294 ft^2 of array area). This size of the collector could provide all daily DHW requirement for the case-study house (Rasisuttha, 2004).

Strategy 11: Generate on-site electricity which was produced by a PV system (no thermal energy collected). The PV array’s area was 1,053 ft^2 which was all available area of the roof.

Strategy 12: Combination of strategy 10 and 11. This strategy was similar to Strategy 10 that installed 294 ft^2 of the hybrid PV-T^2 array. However, in this strategy, in addition to the hybrid PV-T^2 arrays, PV arrays were installed on the remaining area of the roof (759 ft^2) to increase electricity generation.

Combination A: Combine strategies 2, 3-4, 7, 8, and 9.

Combination B: Combination A + Strategy 4 (low-e windows).

Combination C: Combination A + Strategy 5 (shading devices).

Combination D: Combination A + Strategies 4 and 5.

Combination E: Combination D with PV-T^2 collector system.
Combination F: Combination D with photovoltaic system.
Combination G: Combination D with PV-T^2 collector system and photovoltaic system.

Calibration of the Base-Case Model

Simulated energy use and space temperatures in the case study buildings were calibrated to match the actual energy use, and the measured space temperatures in order to make the model accurately perform like the real building. Two comparisons were used for the calibration:

1) Average monthly electricity use including DHW energy use. This was a comparison between the actual monthly electricity used from the electric utility bills and the monthly electricity use from the DOE-2 simulation. Estimated DHW energy use, using the schedule obtained from the residents, was also used to compared with the simulated DHW energy use. Figure 3 presents the results of the calibrated monthly energy use, and domestic hot water (DHW) energy use.

2) Hourly zone temperatures. Measured temperatures in the unconditioned spaces and the air-conditioned spaces of the case-study house were compared with the simulated model's zone temperatures.

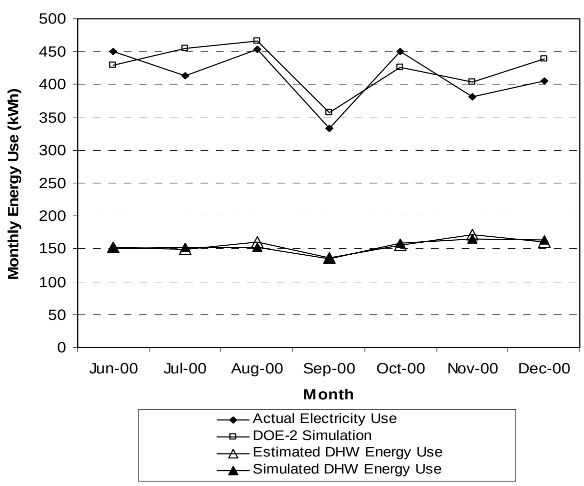


Figure 3: Comparison between the Actual and the Calibrated Simulated Electricity Use, including the Domestic Hot Water Energy Use from June to December, 2000.

Figures 4 and 5 present a two-week time-series plot of both measured and the calibrated zone temperatures in four spaces of the case-study house (i.e., the living room, the master bedroom, bedroom-3, and the attic).

A field experiment of the PV-T^2 system was constructed to test its ability to simultaneously produce electricity and hot water, as well as the ability to reject heat during the evening (Rasisuttha 2004). The resultant electricity and hot water production from the hybrid PV-T^2 collector system helped reduce the use of non-renewable energy. The evaluation of the case study house and results of the field experiment helped quantify the potential reduction of energy use in Thai residential buildings.

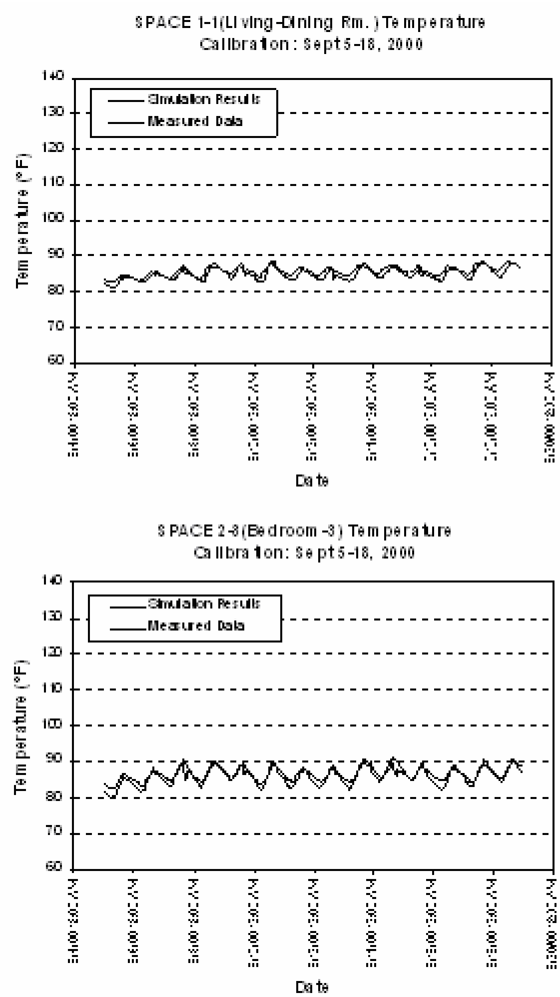


Figure 4: Comparison Between the Measured and the Calibrated Simulated Temperatures of the Living-Dining Room and Bedroom-3 (Both were unconditioned space).

This research used the F-CHART (Klein and Beckman, 1981) and PV F-CHART (Klein and Beckman, 2001) programs to analyze the thermal and electrical energy produced by the Hybrid PV-T^2 collector system to integrate the results into the simulation of the case-study house. The F-CHART program was used to assess the thermal energy produced by the Hybrid PV-T^2 for the case-study house, which was located in Thailand.

The test slope (FrUL) and test intercept ($Fr\tau\alpha$) parameters, which were used in the analysis were determined from experimental results (Rasisuttha, 2004). Electricity generation rates were determined from the experiments for varying panel temperatures and used in the PV F-CHART program.

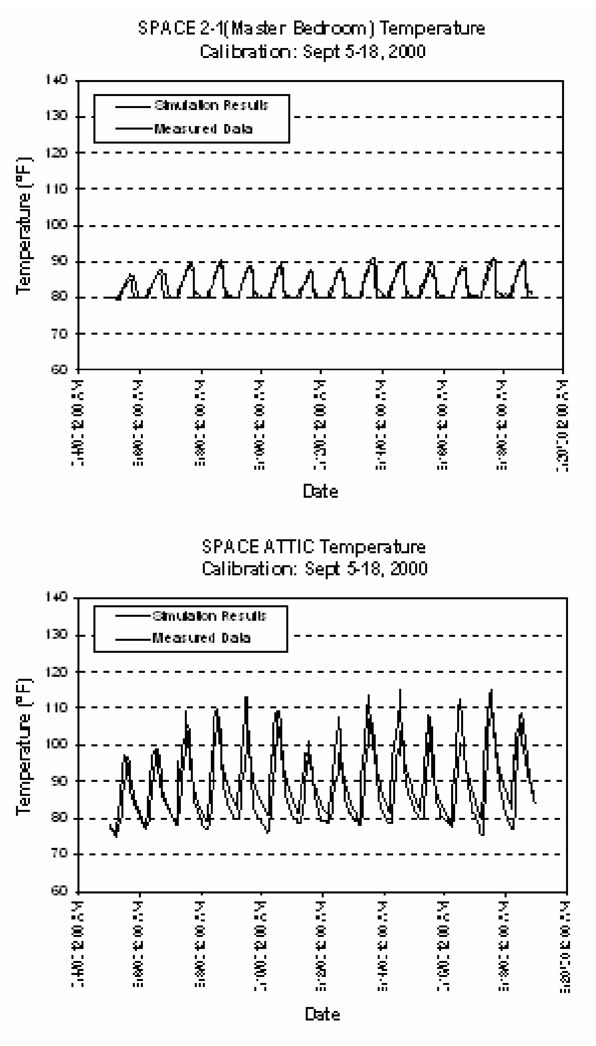


Figure 5: Comparison Between the Measured and the Calibrated Simulated Temperatures of the Master Bedroom (A/C was operated only in the nighttime (from 7:00 p.m. to 7:00 a.m.) and the Attic.

Economic analyses of the case-study house were used to compare the base-case building with the same building improved by the energy efficiency strategies and renewable energy technologies using the annualized life-cycle cost analysis method described in ASHRAE Handbook (ASHRAE, 1999; Haberl, 1993).

RESULTS

Measured Space Temperatures in the Case-study House

The living room, bedroom-3 and attic are all unconditioned spaces in the case study house. However, these spaces are on different floors and orientations of the building. The living room is on the first floor and has exterior walls in almost every direction (i.e., south, east and west). Bedroom-3 is on the second floor and has only two exterior walls; west and north walls. However, bedroom-3 is also under the attic.

From Figure 6, the outdoor temperatures can be seen to cover a wider range than the indoor spaces except the attic, which has higher temperatures. The range of outdoor temperatures (highest temperature – lowest temperature) was 32 °F; while the indoor temperatures of the unconditioned living space are in narrower ranges (17 °F and 21.5 °F for living room and bedroom-3, respectively). The outdoor temperatures, however, have no dominant temperatures, while the indoor temperatures of the living room and bedroom-3 have dominant temperatures. The measured temperatures that occurred most often in the living room and bedroom-3 were 83-86 °F and 85-88 °F respectively, so bedroom-3, which was on the second floor, was hotter than the living room. However, the frequency of the dominant temperature of the living room was higher than that of bedroom-3. Conversely, for the attic, temperature conditions varied over a much wider range than that of the outdoors, especially at higher temperatures. The attic temperatures reached the maximum temperature range of 115-116 °F, while the highest outdoor temperatures were in the range of 95-96 °F.

For the conditioned space, the master bedroom had a range of temperatures very close to that of bedroom-3 which is also on the second floor. However, the most frequent temperatures of the master bedroom were in the range of 79 to 82 °F, which is lower than that of bedroom-3 (85-88 °F). This difference is most certainly because of the operation of the master bedroom's air-conditioning system during the evening hours. The most frequent temperature range of the master bedroom accounted for approximately one half of the total hours of the measured data (2,600 hours of temperatures in the range of 79 to 82 °F to the total of 5,136 hours). This confirms that the master bedroom's air-conditioning system was operated about 12 hours per day as scheduled. In general, the indoor temperatures

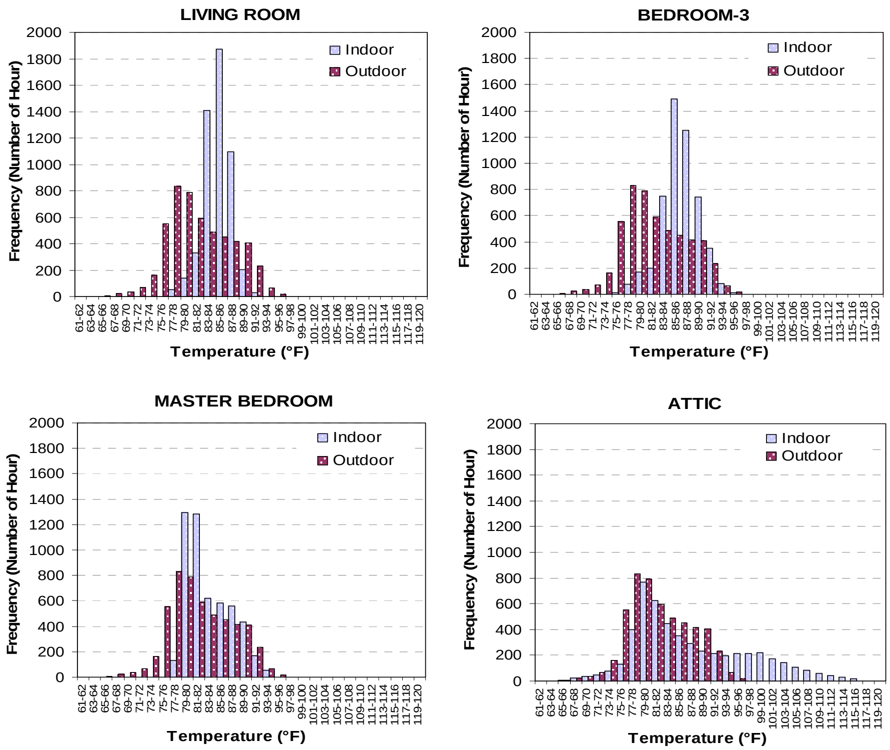


Figure 6: Histogram Plots Measured Temperature Conditions in the Case-Study House's Space (June-December, 2000).

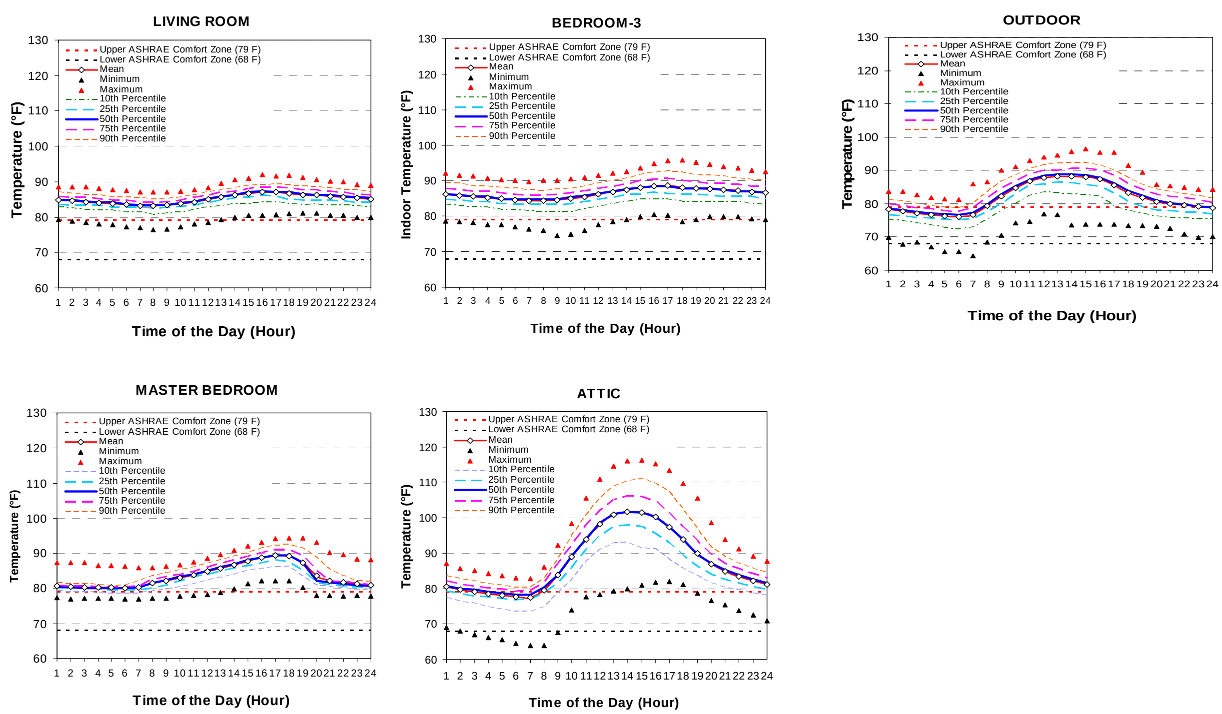


Figure 7: 24-hour Temperature Profiles in the Case Study House (June – December 2000).

(except in the attic) have less variability than the outdoor temperatures.

The 24-hour temperature profiles of the indoor spaces in the case-study house are shown in Figure 7. The 24-hour temperature profiles of the living room and bedroom-3 show similar 24-hour the patterns (i.e., the swing temperatures). In both spaces, the temperatures reach the lowest point in the morning about 7:00 to 8:00 a.m., and reach the highest point in the afternoon (i.e., about 3:00 p.m. for the living room and at about 4:00 p.m. for bedroom-3). The difference in the range of hourly temperatures of both spaces seems to suggest the influence of the ground coupling, since living room is on the first floor, where it is coupled to the ground, and bedroom-3 is on the second floor.

The daily temperature profile of the attic shows the expected differences between temperature conditions in the daytime versus the nighttime. The attic's mean temperature reached its lowest point of about 78 °F in the morning (about 7:00 a.m.), and rose rapidly to the reach its highest point of about 102 °F at about 1:00 p.m. to 2:00 p.m. The temperature declined after 2:00 p.m., but was still relatively high in the afternoon and the evening compared to the outdoor mean temperatures. The mean temperatures of the attic from 3:00 p.m. to 6:00 p.m. were between 90 °F to 100 °F, while the outdoor mean temperatures in the same period were between about 82°F to 88 °F. After 6:00 p.m. the attic's temperatures were still higher than the outdoor temperatures. The peak of the attic's temperature profile in the daytime (at 2:00 p.m.) showed that solar radiation played a very significant role in the temperature of the attic. The relative high temperatures of the attic after the sunset shows the thermal delay caused by the high thermal mass roof and attic walls, which are the main components of the roof.

The daily temperature profile of the master bedroom was the only profile of an air-conditioned space (Figure 7). From the air-conditioning's systems operating schedule, which was obtained from the residents, the air-conditioning system of the master bedroom was operated only during the nighttime (from 7:00 p.m. to 7:00 a.m.). The residents reported that the setpoint temperature of the thermostat was 26 °C (78.8 °F), which is confirmed by the measured data. The profile showed a relatively flat profile during the air-conditioned period, with the space reaching the setpoint within two or three hours.

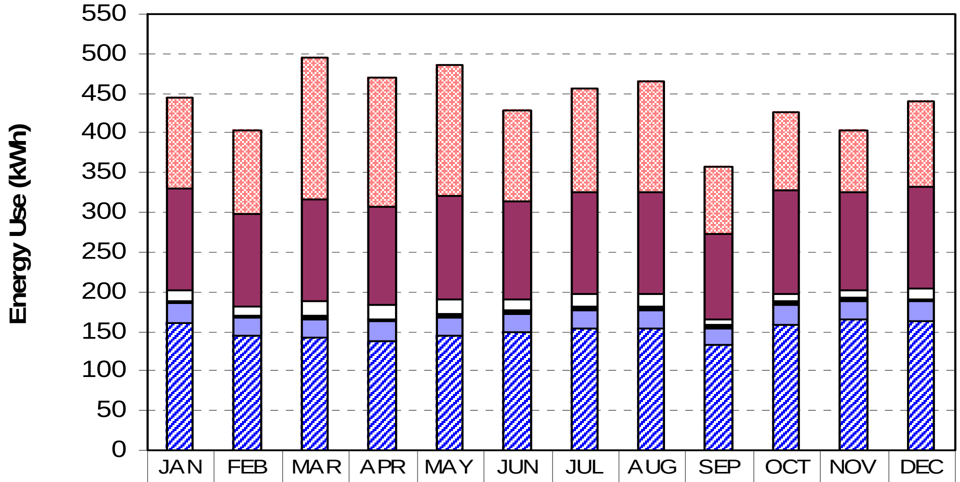
The mean temperature in the air-conditioned period is about 81°F, which is slightly higher than the thermostat setpoint. This may be caused by the placement of the data logger, since the data logger was placed on an interior wall that was a partition between the master bedroom and the hall, which is an unconditioned space on the second floor. Although there were no data loggers placed in the hall, the hall is adjacent to bedroom-3 and both were unconditioned. Furthermore, there is a refrigerator in the hall on the second floor. Therefore, temperatures in the hall, during the master bedroom's conditioned period, were assumed to be slightly higher than the temperatures in the bedroom-3. The mean temperatures of the bedroom-3 varied approximately from 84 °F to 87 °F during the period that the master bedroom was conditioned (from 7:00 p.m. to 7:00 a.m.). Thus, there were temperature differences of about 5 to 9 °F between the conditioned and unconditioned spaces. This was believed to be the reason for the consistently high logger readings.

DOE-2 Output of the Base-case House

Figure 8 presents the results of the base-case DOE-2 simulation. From the figure, the DHW heater, air-conditioning systems (including ventilation fan), and equipment consumed approximately 34, 31, and 28 percent of the total energy consumption, respectively. Thus, these three sectors were significant to the total energy consumption, especially the energy used by water heater, which accounted for approximately one-third of the total energy consumption per month.

Results of the Simulation of the Energy Efficiency Strategies

The results of Strategies 1-12 and Combinations A-G are compared in Figure 9. From the figure, for the individual energy efficiency strategies excluding Strategies 10 to 12, Strategy 3-4 (insulated light-weight concrete block walls) was the most effective single strategy (9.08 percent of total energy reduction). Strategies 3-1, 3-2, 3-3 were also very effective. For the energy reductions that include the renewable energy technologies (Strategies 10 to 12) as compared to the individual energy efficiency strategies, Strategy 12, which is the combined PV-T^2 and PV systems, was ranked in first place (51.37 percent of the base-case building's energy use). The PV-T^2 collector system (Strategy 10) and the PV system (Strategy 11) were ranked in the second place and third place, respectively (a reduction of 43.25 percent and 23.30 percent of the building's energy use, respectively). Combination G was ranked in 1st place in the combined analsys, which was able to reduce the building's energy use by 72.58



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Cooling (kWh)	113	106	178	161	166	115	130	141	84	100	79	107
Equipment (kWh)	129	116	128	125	129	124	129	128	107	129	124	129
Vent Fans (kWh)	13	12	19	17	19	13	15	16	9	11	9	12
Pump (kWh)	4	3	4	4	4	4	4	4	3	4	4	4
Lighting (kWh)	24	22	24	24	24	23	24	24	20	24	23	24
DHW (kWh)	161	145	142	138	144	150	153	153	134	159	165	163

Figure 8: Base-case Monthly Energy Use from the DOE-2 Simulation: January to December, 2000

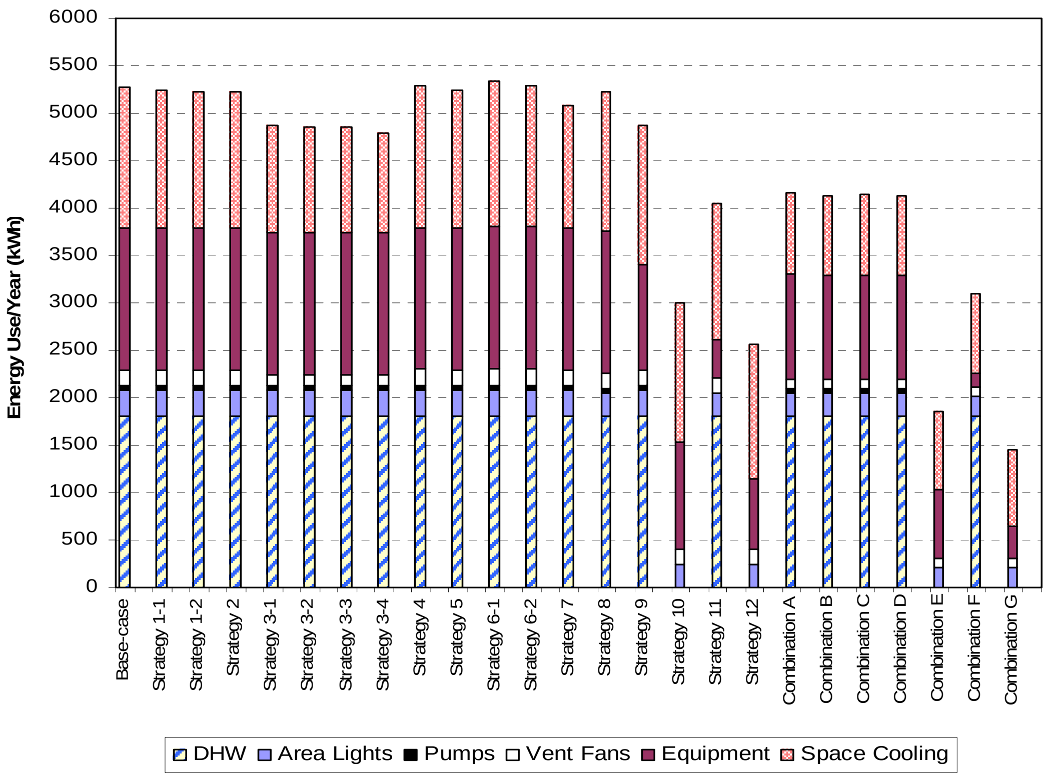


Figure 9: Comparison of Annual Energy Consumption of the Base-Case and Energy Efficiency Measures: January to December, 2000

percent. Combination E and F were ranked in the 2nd and 3rd (64.92 and 41.35 percent of the base-case use, respectively) for the combined analysis. From these analyses, it is clear that achieving a zero net energy house in Thailand could be accomplished with an additional modest investment.

Results of Economic Analysis

An annualized life-cycle cost analysis of the case-study house, which included energy efficiency strategies and the renewable energy technologies was preformed (Rasisuttha 2004). The annualized life-cycle costs of the base-case house as compared to Strategies 1 to 12 and Combinations A to G are presented in Figures 10 and 11. The results from the analysis showed that the lowest annualized life-cycle cost ($3,481) was achieved by Strategy 9 which was the replacement of new

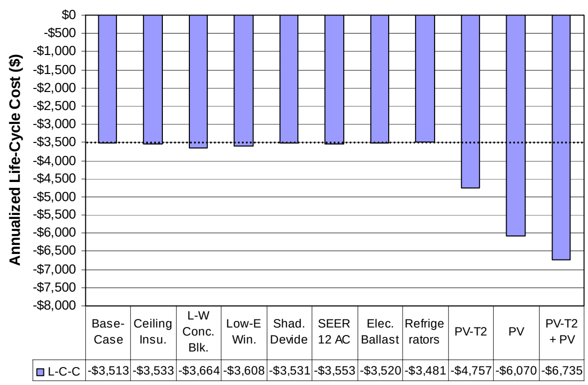


Figure 10: Annualized Life-Cycle Cost of the Individual Energy Efficiency Strategies and the Renewable Energy Systems

refrigerators. Strategy 9 not only yielded the lowest annualized life-cycle cost, but it was also the only strategy that had an annualized life-cycle cost that was lower than the base-case. The results of monthly payments of the energy efficiency strategies showed that the estimated monthly payments were not significantly higher than that of the base-case house. This suggests that, in the current economic scenario, improving the base-case house using the energy efficiency strategies (except renewable energy systems —Strategies 10 to 12 and Combinations E to G) should be acceptable to Thailand consumer, since the monthly payments are approximately equal to the payments of a traditional house.

SUMMARY

Thermal conditions and building energy use in a case-study residence in Thailand have been investigated through measurement and simulation. The results of simulated energy reduction from the application of several energy efficiency strategies including renewable energy systems were reported. In summary, for the individual energy efficiency strategies (excluding the renewable energy systems), Strategy 3-4 (insulated light-weight concrete block walls) was the most effective strategies, yielding a 9.08 percent reduction in total energy. However, Strategy 9 (highly energy efficient refrigerators) yielded the lowest annualized

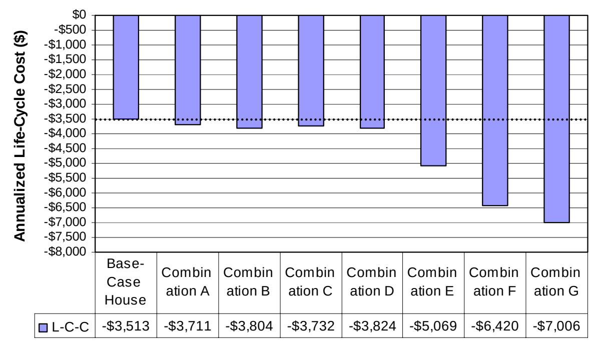


Figure 11: Annualized Life-Cycle Cost of the Combined Energy Efficiency Strategies (Combinations A to G)

life-cycle cost among all individual energy efficiency and combinations of measures including renewable energy strategies. Combination G, which includes all strategies, and solar thermal and PV, is capable of reducing the annual energy use by 72.58%, however it has the highest annualized life-cycle cost.

REFERENCES

ASHRAE 1999. ASHRAE Handbook - HVAC Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA.

EIA 2003. International Energy Outlook 2003, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

DEDP 1998. Thailand Energy Situation 1998, Department of Energy Development and Promotion, Ministry of Science, Technology and Environment, Thailand.

Duffie J. A. and Beckman W. A. 1991. Solar Engineering of Thermal Processes, Wiley, New York.

Haberl, J. S. 1993. Economic Calculations for ASHRAE handbook. Energy Systems Laboratory Report EST-TR-93/04-07, College Station, TX: Texas A&M University.

Huang, J. 1994. DrawBDL: Version 2.02, Joe Huang and Associates, El Cerrito, CA.

Klein S.A. and Beckman W.A. 1981. F-Chart User's Manual Microcomputer Version, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

Klein S.A. and Beckman W.A. 2001. PV F-Chart User's Manual Windows Version, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

LBNL 1982. The DOE-2 Reference Manual Version 2.1A, Lawrence Berkeley National Laboratory, Berkeley, CA.

LBNL 2000. DOE-2.1e, ver. 107, Documentation Update Package #2, Simulation Research Group, Lawrence Berkeley National Laboratory, University of California at Berkeley, Berkeley, CA, (March).

NSO 1996. Report on Housing Survey 1996, National Statistical Office, Bangkok, Thailand.

Rasisuttha, S. 2004. The Development of Improved Energy Efficient Housing for Thailand Utilizing Renewable Energy Technology. Doctor's Dissertation, Texas A&M University, College Station, TX (in preparation).

Rockendorf G., Silimann R., Podlowski L., and Litzenburger B. 1999. PV-Hybrid and Thermoelectric Collectors, Solar Energy 67 (4-6), 227-237.

TGP 1996. Energy Efficient Design of Buildings in Thailand, Thai Gypsum Products Public Company Ltd, Bangkok, Thailand.