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From Comfort to Kilowatts: An Integrated Assessment of Electricity Conservation in Thailand's Commercial Sector

Author

Busch, J.F.

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J.F. Busch, Jr.
(Ph.D. Thesis)

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DISCLAIMER

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FROM COMFORT TO KILOWATTS: AN INTEGRATED ASSESSMENT OF ELECTRICITY CONSERVATION IN THAILAND'S COMMERCIAL SECTOR

(*Doctoral Dissertation*)†

John Franklin Busch, Jr.

Energy Analysis Program
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 USA

August 1990

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† Dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Energy and Resources Group, University of California, Berkeley.

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Dedication

To my family, whose backing I could always count on.

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Even beginning to enumerate all the people who played a role in bringing this dissertation to fruition is a daunting task. Undoubtably many contributors will slip through my seine as I now haul it out, but they are nonetheless warmly appreciated, albeit anonymously.

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Friendship and assistance in a foreign land is a special gift, particularly when one is engaged in otherwise lonely pursuits. Unusual warmth and insights were shared by my two principal Thai sponsors, Professors Pibool Hungspreug and Surapong Chirarattananon of King Mongkut's Institute of Technology, Thonburi (KMITT). Boonpong Kijwatanachai of MITR Technical Consultant Co. helped me in ways measurable and not: he helped in selecting the Bangkok buildings I studied, in obtaining permission to survey those buildings (no small feat), and in gathering and interpreting the building data. In retrospect, I can safely say that without his help I would not have had as much success in this work.

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From Comfort to Kilowatts: An Integrated Assessment of Electricity Conservation in Thailand's Commercial Sector

John F. Busch

ABSTRACT

Thailand serves as a case study of the potential to conserve electricity in the fast-growing commercial sectors of the tropical developing world.

We performed a field study of over 1100 Thai office workers in which a questionnaire survey and simultaneous physical measurements were taken. Both air-conditioned and non-air-conditioned buildings were included. We analyzed Thai subjective responses on the ASHRAE, McIntyre and other rating scales, relating them to Effective Temperature, demographics, and to rational indices of warmth such as PMV and TSENS. These results suggest that without sacrificing comfort, significant energy conservation opportunities exist through the relaxation of upper space temperature limits.

To investigate the potential for conserving energy in a cost-effective manner, we performed a series of parametric simulations using the DOE-2.1D computer program on three commercial building prototypes based on actual buildings in Bangkok; an office, a hotel, and a shopping center. We investigated a wide range of energy conservation measures appropriate for each building type, from architectural measures to HVAC equipment and control solutions. The best measures applied in combination into high efficiency cases can generate energy savings in excess of 50%. Economic analyses performed for the high efficiency cases, resulted in costs of conserved energy of less than and internal rates of return in excess of 40%. Thermal cool storage, cogeneration, and gas cooling technology showed promise as cost-effective electric load management strategies.

Drawing on the building energy simulation results, impacts on the Thai electric utility were evaluated under various conservation scenarios. The scenarios were represented by four technology packages at different degrees of penetration in the sector: high-efficiency, building energy standard, non-electric cooling, and thermal energy storage. Simulation of the power system to the year 2006 under these scenarios using the ELFIN utility planning model revealed substantial cost and reliability benefits of conservation to the Thai utility. Furthermore, the conservation scenarios allow the utility to defer or cancel a significant amount of capacity planned for future inclusion in the system. Comparison of the capital requirements of the conservation scenarios versus the deferrable plant capacity, showed that conservation was one quarter as capital intensive.

CHAPTER 1

Introduction

Consumption of electricity, typically the most expensive form of commercial energy, is increasing rapidly in developing countries. While industrialization and rising affluence of the populace are largely responsible for these new demands on the power sector, increasingly, the demand from large commercial buildings in burgeoning cities accounts for an ever larger share of total commercial energy use. This is especially true of air-conditioned buildings located in hot and humid equatorial countries. Demand for electricity from air-conditioning systems contributes significantly to an electric utility's peak load, leading to greater investments in generating capacity or necessitating power curtailments, both of which have a high social cost. Because the provision of electricity services in these countries is largely dependent upon foreign capital and imported fossil fuels, it consumes foreign exchange that could be put to other uses. For this reason, energy-conservation in air-conditioning is a significant developmental strategy.

However, this strategy has not been exploited. This can be explained in part by two prevailing assumptions shared by many development analysts: 1) that a direct positive relationship exists between energy use and economic well-being; and 2) that there are few opportunities for saving energy in a cost-effective manner in societies that use on the order of 20 times less per-capita energy than the U.S. Both of these notions have been challenged in the literature [Dunkerley et al. 1981; Goldemberg et al. 1985a; Geller 1986; Geller 1984].

Nonetheless, hot and humid climates do present a particular challenge for building design. Many passive cooling techniques that work in other climates are ineffective in tropical conditions. Natural ventilation is the only passive cooling strategy with potential to deal with this climate, yet it too suffers from several limitations. One such limitation is imposed by the physical layout of cities, which is dictated by economics and other considerations, but rarely takes advantage of prevailing wind patterns. Instead, buildings generally interfere with each other's wind resource. Likewise, building interiors designed to meet functional needs, principally through interior partitioning, impede the flow of air. In addition, other factors involving the interaction of the exterior and interior environments also can adversely affect potential for natural ventilation. For example, street level noise is often cited as a motivation for window aperature closure and the subsequent need to air-condition. Emerging work patterns, the adoption of more formal (and hotter) Western dress, and changing expectations also contribute to the growth of air-conditioning.

In the last 15 years, conservation efforts in the industrialized countries have brought significant gains in economic efficiency and improved environmental quality. The lessons learned by these countries have not yet been transferred to the developing world, partly because of contextual differences. For instance, much of the conservation research in buildings has focussed on curtailing energy use for heating, an irrelevant issue for most developing countries, which are located in the tropics. Other challenges to energy saving efforts in developing countries include rapid urbanization and economic growth, extreme hot and humid climatic conditions, scarce natural resources, and limited capital.

THAILAND AS A CASE STUDY

Thailand offers an interesting case study of the potential for energy conservation in tropical developing countries because of its climate, size, stage of development, and rapidly growing electricity sector. Located in the heart of peninsular Southeast Asia, Thailand covers 514 thousand square kilometers (an area roughly 20 percent larger than the state of California), stretching from the northern hills at 20 degrees north latitude to a narrow isthmus sandwiched between the Gulf of Siam and the Andaman Sea at 6 degrees north latitude. By 1988, the population was 54 million, with a growth rate of 2 percent per year [World Bank, 1989]. This populace, while still largely rural, nonetheless shifted significantly to urban areas in the last few decades, mirroring a large transformation of the economy.

Bangkok, the capital and largest city with roughly 6 million residents, has absorbed nearly three quarters of all urbanization in Thailand. An indication of Bangkok's primacy as an urban center is its size relative to the next largest city (Chiang Mai), which has a population of less than 200,000 [NSO 1989]. Once an agrarian economy based primarily on rice, the Thai economy has diversified into manufacturing and commerce with jewelry, textiles, food processing, and component assembly of automobiles as major industries. Considered a "middle income country" by the World Bank on the basis of per capital income, Thailand's gross national product (GNP) per capita in 1987 was 850 U.S. dollars equivalent with a growth rate exceeding ten percent, the world's highest.

The commercial sector has emerged out of the general growth and diversification of the economy. This sector accounts for half of the GNP, and has the highest rate of growth, well ahead of the industrial and agricultural sectors. Within the commercial sector, banking, wholesale and retail trade, and tourism are major activities. All of this economic activity occurs within buildings that are increasingly equipped with air-conditioning. Thus, as the commercial sector grows, so does its electricity demand. In step with the economic boom, the power sector in Thailand has experienced phenomenal growth in demand, averaging 15 percent per year over the last two years.

MOTIVATION FOR CONSERVING ENERGY

Energy conservation can play a critical role in the larger context of national development. Thailand is embarking on an energetic economic development process. This process depends in large part on energy, or more precisely, on the services that energy provides. Our discussion here emphasizes that energy conservation is indeed compatible with other stated goals, and that it achieves those goals in a more efficient and benign manner than traditional uses of energy. Moreover, energy conservation enhances the public interest by improving commercial competitiveness in the international arena, environmental quality, and capital availability.

Commercial Competitiveness

In a competitive market, firms strive to allocate resources -- capital, labor, energy -- to minimize costs and maximize production and performance. Resource allocation is seldom optimal because markets are imperfect, but the general lesson still holds that firms must keep costs down to be competitive. For Thai commercial entities, energy costs are probably a disproportionately large share of total costs. While low labor costs have helped Thai firms maintain a strong position in the international arena, inevitable demands for higher wages will erode this cost advantage. Thus, for Thai commercial firms to remain competitive, particularly in export activities, they should begin to use energy more efficiently by substituting capital for energy in an optimal way.

The balance of imports and exports measures national competitiveness, and energy conservation can be a key factor. Large energy imports can negatively affect the Thai economy in two respects: 1) as a direct debit to the trade account; and 2) as a reduction of exports from sectors with high costs due to wasteful energy use. The actual trade balance would ultimately depend on the relationship between energy use and economic output.

Environment

Energy use is a major cause of the environmental degradation associated with modernization. Combustion of fossil fuels contributes heavily to air pollution, much of it a result of power generation. An analysis of emissions of an inventory of pollutants in Thailand has estimated that power generation by the electric utility accounts for one-third of the suspended particulate matter and nitrous oxides, and half of sulfur dioxides [TDRI, 1987]. The latter two pollutants are the main constituents in acid rain. Acidification of Thai water or land resources is already evident, and given the widely confirmed correlation of acid rain effects with the continued emission of these constituents, greater acidification is very likely. Acidification renders water bodies and soils less able to support life, mobilizes other toxics like aluminum, and has been implicated in the demise of large forested areas in Europe. Were acid rain to similarly affect the already beleaguered tropical rain forests, this would represent another major concern.

Fossil fuel burning, along with deforestation, are largely responsible for the increase in carbon dioxide in the atmosphere now linked to the potential for global climate change. Thailand faces a particular risk from global warming since one probable outcome is a dramatic rise in sea level due to melting of the polar icecaps and seawater expansion, which could inundate Bangkok and force its abandonment (but which would finally resolve its traffic congestion problem).

In addition to fossil fuels, the Thai utility relies on the potential energy of flowing rivers to supply its generators. Hydropower also imposes environmental and social costs. In some cases, vast fertile stretches of land and, often, active villages are inundated by reservoirs; in others, dams located in remote, forested areas have, through the construction of access roads, attracted illegal timber harvesting. The ecology of the riparian basins is irreversibly changed by altered flow regimes due to a dam project. Furthermore, Thailand's famous chocolate-brown rivers transport silt and suspended matter that precipitate out in the static water of downstream reservoirs, and diminish the useful life of dam projects. As observers of the Thai scene will attest, the Thai environmental movement arose, in part, out of concern about the impacts of the utility's proposed Nam Choan dam on the Thung Yai Wildlife Sanctuary, causing a public outcry uncustomarily shrill in Thai discourse.

Policy and regulatory measures designed to curtail use of energy can play a significant part in minimizing these types of environmental effects.

Capital Constraints

It might be argued that a key characteristic of developing economies is a chronic shortage of investment capital. In the energy sector, particularly the power sub-sector, capital needs are enormous. At the outset of the 5-year economic plan ending in 1991, the Thai electric utility was budgeted 80% of total public investment in energy. The current power development plan calls for investment in plants and transmission projects exceeding $ 25 billion (U.S.) through 2006, more than half of which is to come from foreign borrowing. The foreign capital portion, amounting to $ 750 million, comprises a major portion of the annual public foreign debt ceiling for *all* purposes now set at $ 1.2 billion. In a country growing as rapidly as Thailand is now, conflict between huge power sector capital demands and other infrastructure needs, such as ports, public transport, communications, etc., can be quite serious.

The capital crunch in the power sector could be eased, by investment in energy conservation to displace investment in power plants and transmission networks. Energy conservation investment requirements are typically much less that of equivalent power sector investment. A notable barrier to realizing these capital savings is the disparity in the perspectives of the utility, consumer, and society. Conservation serves the economic interest of consumers and society through cost-effective investment, freer capital markets, and environmental sustainability. For the utility, however, commercial sector conservation often is not perceived as serving its economic interest because of the foregone revenues through lost sales to commercial customers who pay relatively high prices for electricity.

In sum, the challenge for public policy is to promote the larger social interest in energy conservation by overcoming market externalities, such as pollution and capital shortages, that impinge on economic productivity and human and environmental health, while also maintaining the viability of the crucial power sector.

APPROACH

The research approach taken here is characterized by three distinct features. The first is the focus on the end-use level of energy use. Analysis of energy issues traditionally has focussed on supply-side options to meet a growing, almost amorphous demand. The oil crisis of the early 70's challenged this approach and inspired new ways of assessing the overall energy picture. Among these, the realization that energy is not important for its own sake but for the services it provides prompted analysts to begin to focus on those services, or end-uses, to discover significant opportunities for improving their efficiencies. One major study applied this approach to the world energy context resulting in a forecast of a future scenario far less energy-intensive than previously thought possible [Goldemberg et al. 1985b].

The second distinguishing feature of this research is an emphasis on practicable measures that can be readily adopted and are responsive to energy conservation needs and objectives. The scope of conservation opportunities pursued in this work are those that are attainable with current or emerging technologies. Rather than treating exotic technologies or those "still on the drawing board," attention is given to technologies and policies for implementing and promoting electricity conservation strategies that are: 1) specifically suited to the Thai context, and, 2) can be achieved in the near term, i.e., before the turn of the century.

Finally, research is based on an integrated assessment of energy use and efficiency problems. By analyzing and integrating several levels of the energy conservation problem, this approach reaches across traditional disciplinary boundaries, resulting in a more comprehensive and and context-specific assessment. Briefly stated, state-of-the-art disciplinary methods are employed at each level of analysis, and, where possible, results are incorporated in the disciplinary methods of subsequent analyses. In this way, each analytical step builds towards the broader framework based on the strong disciplinary foundation of all preceding analysis.

Research Questions

Based on the approach just described, our research addresses several levels of analysis that together comprise the necessary framework for assessing energy conservation problems and potential. Specifically, we examine the following:

- What thermal conditions do Thai office workers find comfortable or adequate, given their acclimatization to a tropical climate?
- What are the most promising conservation measures in different types of commercial buildings in Thailand? What is the potential for cost-effective electricity savings?
- What impacts, in terms of operation and investment programs, could be felt by the electric utility under various conservation scenarios, each representing different technology packages and degrees of penetration?
- What are the policy implications for achieving this conservation potential?

ORGANIZATION OF THE DISSERTATION

The body of this dissertation is organized as follows. Chapter 2 presents an analysis of the survey questionnaire responses of Thai office workers regarding their thermal environment, along with physical measurements of that environment. Chapter 3 describes the methodology and results in simulating the energy performance of various conservation measures in prototypical Thai commercial buildings. The impacts on the power sector from scenarios of conservation in the commercial sector are analyzed in Chapter 4. Finally, this dissertation concludes with discussion of the policy implications of conservation in Thailand.

CHAPTER 2

Thermal Responses to the Thai Office Environment

INTRODUCTION

To date the majority of studies of human response to the thermal environment in building interiors have been carried out in the temperate climates of industrialized countries. In this chapter, findings of a field study of thermal comfort in offices in Bangkok, Thailand, are presented. The field study is part of a larger study of energy conservation potential in Thai commercial buildings.

It is important to examine thermal comfort in the context of tropical developing countries because of the concentration of world population and growth there. Currently, air-conditioned buildings in the tropics and elsewhere are designed according to criteria based on comfort studies of white, male, college-age respondents from the West. Because the conditions are so different in most developing countries in terms of race, age distribution, climatic experience, and perhaps expectation, these criteria may be inappropriate. Specifically, there may be opportunities to save energy and capital investment in air-conditioning equipment should there be a preference or higher tolerance of thermal environmental factors such as temperature, humidity, and airflow.

The objectives here are to place the data collected in Thai offices in context by comparison with results of other researchers, particularly those from tropical countries, and to contrast the results from different subgroupings of the data, such as between seasons, between conditioned and un-conditioned buildings, between men and women, and other comparisons where appropriate. Ultimately the goal of this thermal comfort research is to define the limits of tolerance or acceptability of conditions for the purpose of determining energy conservation potential in buildings. The rest of the chapter contains a section on the methods used for gathering and processing the data, followed by discussion of the results and conclusions and recommendations for future work.

METHODOLOGY

In the following section we describe the buildings and how we chose them, followed by our methods for conducting the field survey and carrying out the analysis.

Building Selection

The criteria for selecting buildings for the field study were as follows:

1. located in Bangkok, the capital city of Thailand, where the majority of commercial buildings are,

2. modern buildings not more than ten years old,

3. both air-conditioned (AC) and non-air-conditioned (non-AC) or naturally ventilated (NV) buildings,

4. regular office desk work of a majority of the building occupants,

5. a variety of ages and sexes.

Building Descriptions

The two air-conditioned buildings are of modern high-rise design, one a head office for a bank, the other a multiple-client building. The two naturally ventilated buildings are contemporary medium-rise government buildings housing ministerial and departmental offices. All buildings are located within ten kilometers of one another in downtown Bangkok.

Data Collection

Thailand experiences three distinct seasons in a year. The studies reported in this chapter were carried out in each of two seasons: during the hot season (in April) and the wet season (in July) of 1988. Each of the four buildings mentioned above were visited in both seasons. Data were typically collected over one work-week at each site per season.

Questionnaire. The questionnaire consisted of a section of subjective ratings on a variety of thermal scales, followed by a section on recent food and beverage consumption, then separate clothing lists for men and women, and concluded with a section on demographic factors. Subjective ratings employed the seven-point ASHRAE Thermal Sensation Scale shown in Figure 2A. Respondents were asked to mark the scale at any one of the seven points or the mid-points in between them (i.e., at any "tick mark"). Another seven-point scale, the Bedford Scale, was not used in this study because, though semantically different from the ASHRAE Scale, earlier studies using both produced similar results. The respondents were also asked the question, "I would like to be ..... warmer (1), no change (0), cooler (-1)", otherwise known as the three-point McIntyre Scale. Two further seven-point scales specifically addressing perceptions of airflow and humidity conditions were also used. The questionnaire was translated into the Thai language and scrutinized for semantic accuracy by Thai social scientists with facility in both English and Thai.

Physical Measurements. The measured quantities were dry-bulb temperature, relative humidity, globe temperature, and air velocity. The globe thermometer was fashioned from a thermister and a 38-millimeter diameter ping pong ball painted flat grey. The dry-bulb thermister was shielded by a cylinder of reflective foil. Air velocity was measured with a hot-wire anemometer. All readings were gathered using a datalogger that stored ten-second readings on magnetic tape. The datalogger, tape recorder, and battery (for the hot-wire anemometer) were all contained within, and the temperature and humidity sensors were attached to a wooden box with a handle, similar in size and shape to a standard tool box (see Figure 2B). The hot-wire anemometer was detached from the "tool box" but connected by a two-meter cord. As is evident from Figure 2B, the sensors were attached vertically to maximize exposure to room air and far enough apart to minimize interference with each other. Data for outdoor weather conditions were gathered from measurements made in the city center by the Royal Thai Meteorological Department.

Conduct of the Survey

Teams of two or three typically carried out the survey, with one member taking the physical measurements and one or two handing out and collecting the questionnaire survey forms. The latter would approach prospective respondents and ask if they had been seated at that spot for at least 15 minutes; those who replied affirmatively received the form, the others did not. The questionnaire came with a cover letter explaining the project and the auspices under which it was being carried out, along with general directions for filling out the form. Confidentiality was confirmed and disclosure of respondent's name was optional. An attempt was made not to gather multiple responses from the same individual in a given season, but there was no corresponding effort to exclude people from participating in both seasons. Survey teams sought the participation from a roughly equal proportion of men and women in a range of age and job positions and, to the extent possible, those from different zones and floors of each building.

Measurements of the thermal environment were taken at each workstation following, or in some cases during, the completion of the questionnaire survey form, but usually within five minutes of one another. The "tool box" was placed on or very near the desk where the respondent was seated for at least one minute prior to starting a data sweep. A unique code number for each response was entered into the datalogger and also written on the survey form, along with the starting time of the data sweep to assure proper matching of data sets later. The hot-wire anemometer wand was held at the subject's torso level, as close to the respondent as decorum allowed (i.e., 0.5 meters at a minimum) on the side that intercepted the strongest discernible air flow impinging on the subject. A tell-tale made of thread was used to determine air flow direction. After four minutes of data collection, the "tool box" was shifted to the next workstation. Care was taken to allow the equipment to equilibrate when moving to zones with different temperatures.

Data Processing and Archival

Questionnaire data were numerically coded to facilitate statistical analysis. Individual clothing articles indicated in the survey responses were converted into their respective thermal insulation values (I_{comp}) in units of clo ($1 \text{ clo} = 0.155 \text{ m}^{2°C/W}$) as tabulated in McIntyre (1980). The overall clo value for each subject's entire clothing ensemble was then determined using the following empirical formulae, also from McIntyre (1980),

$$I_{clo,men} = 0.113 + 0.727 \sum I_{comp} \quad (2A)$$

$$I_{clo,women} = 0.05 + 0.77 \sum I_{comp} \quad (2B)$$

Metabolic heat production was not directly measured, but since respondents were carefully pre-screened to have been seated for at least 15 minutes, their metabolic rate was assumed to be 1.1 met ($1 \text{ met} = 58 \text{ W/m}^2$), which is the typical level given for light office activities (ASHRAE 1989). Later computation of various comfort indices required determining the body surface area (A_{Du}) of each subject in square meters based on their reported weight (W) and height (H) (in kilograms and meters, respectively) using the Dubois formula (McIntyre 1980),

$$A_{Du} = 0.202\, W^{0.425}\, H^{0.725} \quad (2C)$$

Mean radiant temperature (MRT) was calculated as prescribed in the 1984 ASHRAE Systems. A program adapted from the Doherty and Arens (1988) model for calculating environmental indices such as ET* and SET* and comfort indices such as PMV*, HSI, DISC, and TSENS. Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) were calculated using the method specified in the International Standards Organization Standard 7730 (1984).

Physical measurements were transferred from cassette tape to microcomputer files. Then non-linear analog sensor outputs were converted into physical units and all outputs processed into averages of three minutes' data for each workstation. These physical measurement data along with the questionnaire data were entered into microcomputer databases for subsequent analysis and archival.

RESULTS

Profile of the Sample

The total sample of responses numbered 1146 drawn from office workers in four buildings[1] during each of two seasons. Of these, 669 were women and 476 were men. Six hundred responses were obtained in the hot season and 546 in the wet season. In each season nobody was surveyed more than once, but some portion[2] of the respondents participated in both seasons. Two-thirds of the sample comes from the air-conditioned buildings (757) while the rest (389) were taken from naturally ventilated buildings. The distribution of ages in the sample are shown in Figure 2C. The age of the sample ranges from 18 to 75 years and has a mean of 32. The highest education attained was the Thai equivalent of high school for 431 of the respondents, a bachelor's degree for 586, and a post-graduate degree for 122. The overwhelming majority (1003) of respondents listed themselves in the lower category of job positions with 127 in middle positions and only nine in upper positions. Because the sample included people from private sector businesses and professional firms, government civil services, and universities, the survey question dealing with job rank was necessarily general and subject to interpretation in each situation. It is also possible that customary Thai modesty has skewed the choice of job rank lower.

The distribution of measured physical data is shown in Tables 2A and 2B broken down by building and season. Clo values ranged from 0.24 to 1.19 averaging 0.53 in both seasons. Figure 2D shows two histograms depicting the clo values for men (in the foreground) and women (in the background). Women had much more varied thermal insulation in their attire. The average Dubois body surface area (not shown in Table 2A) for the entire Thai sample was 1.56 m^2 with a standard deviation of 0.17 and a range from 0.62 to 2.58 m^2. Air temperatures ranged from a low of 19.5°C in an air-conditioned building to a high of 34.2°C in a naturally ventilated building, averaging around 26°C for the sample with little difference between the hot and wet seasons. Vapor pressures reached a high of 28.4 Torr and went as low as 6.9 Torr, averaging 16.9 Torr, again with little seasonality. Air-conditioned buildings had an average air-velocity of 0.13 m/s while naturally ventilated buildings experienced higher airflows of 0.33 m/s on average. Because the latter buildings also utilized local fans, air velocities at the workstation went up as high as 2.25 m/s. From these data we calculated the ASHRAE Effective Temperature (ET*), defined as that temperature at 50% relative humidity, mean radiant temperature equal to air temperature, and air-velocity of 0.1 m/s that would produce the same thermal sensation as the actual environment. The resultant ET* averaged 27.5°C for the entire sample extending up to 36°C and down to 20.5°C. Figure 2E is a frequency distribution of ET* with the hot and wet seasons depicted. The bi-modal separation of the data between air-conditioned and naturally ventilated buildings in each season is clearly evident.

Distribution of ASHRAE and McIntyre Scale Responses

The survey participants cast their votes on the seven-point ASHRAE Thermal Sensation and three-point McIntyre scales in response to the immediate conditions at their desks. The distribution of votes for both scales is shown in Figures 2F through 2H. Almost 35% of the votes were cast in the ASHRAE Scale zero category (e.g., "neutral") and three-quarters voted within the central three categories (between "slightly cool" and "slightly warm" or -1 and 1 on the

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[1] One additional building served in a single-day pilot study in the hot season and the 25 responses from that building are included in the analysis.

[2] For reasons of confidentiality, participant names were not tracked and therefore an exact figure of multiple-season respondents cannot be calculated.

scale). Few people chose to indicate their thermal sensation in the half-steps between whole-numbered categories. The ASHRAE Scale votes were not appreciably different between the hot or wet seasons as shown in Figure 2F where they are juxtaposed. However, the distribution of votes is quite different for AC versus NV buildings. They are compared in Figure 2G. Almost 90% of the respondents in AC buildings selected between "slightly cool" and "slightly warm," whereas only about 57% of the NV building respondents did so. Responses to the McIntyre Scale (graphed in Figure 2H) overall were 42% preferring "no change," 52% for "cooler," and 6% for "warmer." In the hot season, slightly more shifted their votes from the other two categories to "cooler" for a total of 58%. "Cooler" and "no change" had an equal percentage of the votes in the wet season at 45%, with slightly more preferring it warmer. Again, the biggest contrast exists between the samples in AC and NV buildings. Seventy-eight percent of the NV votes fell into the "cooler" category, whereas the fraction was 38% in the AC case. "No change" was the stated preference of 52% in the AC buildings, where only 20% chose similarly in the NV buildings. A surprising 2% voted to be warmer in the NV buildings where temperatures never fell below 25.9°C. Misinterpretation of the question, however, cannot be ruled out.

The scale votes are, of course, taken in response to thermal conditions and therefore are most meaningfully displayed in juxtaposition with relevant environmental variables. In Tables 2C and 2D ET* is cross-tabulated with the ASHRAE and McIntyre scales, respectively. These tables show the percentage of votes at each scale category within 0.5°C ET* ranges (i.e., row-wise percentages). The bi-modal character of the data is clear here with the AC and NV samples overlapping only at ET* of 28°C. The pattern of voting on both the McIntyre and ASHRAE scales alludes to two populations whose thermal sensations (or tolerances or expectations) are distinct from one another.

Mean Responses. The mean of all of the ASHRAE Scale votes is 0.37, or slightly warmer than neutral. On the McIntyre Scale, the mean response is 0.45. Humphreys (1976) regressed such mean responses versus mean air or globe temperatures from 34 field studies worldwide encompassing some 200 thousand observations and got the following relation:

$$\text{Standardized Mean Response} = -0.244 + 0.0166\,T_m \tag{2D}$$

where the mean response is standardized by dividing the absolute mean response by the number of positive categories on the scale. For the Thai sample, the standardized mean ASHRAE scale response is 0.12 (the McIntyre Scale requires no standardization). The above equation predicts 0.19, which is quite close to the mean ASHRAE response but much less so for the mean McIntyre response.

Regression Analysis

Simple linear regression was performed of the mean ASHRAE Scale responses (calculated at 0.5°C ET* intervals) versus ET* to determine the strength of the relationship between them. All of the fits are weighted by the number of votes making up each mean response. Table 2E shows the slope, y-intercept, goodness of fit (R^2), and the number of points going into the fit for various aggregations of the data. The aggregations begin with the entire sample and move toward increased differentiation by season, gender, and space conditioning. For the whole sample, the resultant regression coefficient (slope) is 0.176/°C with an intercept of -4.406 and a high R^2 of 0.91. The regression coefficient is lower than the value of 0.23 found by Humphreys. Schiller's (1988) recent study of air-conditioned environments near San Francisco yielded regression coefficients of 0.328 and 0.308 over winter and summer seasons, respectively. Selecting the Thai data coming only from AC buildings results in a comparable 0.324/°C regression coefficient. Though not true in every case, there is a general tendency for the naturally ventilated samples to have a lower regression coefficient than their air-conditioned counterparts. This is particularly true during the wet season, reflecting perhaps some measure of adjustment or accommodation to prevailing outdoor conditions. The wet season directly follows the hot season in Thailand, giving the people in NV buildings longer exposure to hot and humid weather, and possibly more opportunity to acclimatize than workers in AC buildings. It is also true, however, that the correlations are less strong and based on fewer points in the NV disaggregations. There is a slight difference in the responses of men and women in relation to ET*, with women showing a higher tendency to change their vote due to changes in ET* (i.e., a higher regression slope).

In Table 2F mean ASHRAE Scale responses are regressed against Standard Effective Temperature (SET*), which is defined similarly to ET* but with clothing and activity also standardized. For the Thai data set in particular, because respondents were pre-screened for "standard" activity levels (seated for at least 15 minutes at desk), SET* differs from ET* due to nonstandard clo levels only. Only a subset of the cases regressed on ET* are repeated with SET* and they differ from the ET* results mainly on the slope terms of AC and NV buildings; they are lesser by a factor of two with SET* the independent variable than with ET*. This suggests that voting distinctions between office workers in conditioned and nonconditioned buildings are explained at least in part by differences in clothing. This result confirms our qualitative observation of more informal dress in the NV buildings than in AC buildings and the roughly 0.5 clo calculated difference between them (see Tables 2A and 2B).

It is customary in reporting on thermal comfort field studies to analyze the mean responses as a function of temperature, as has been done above, but regressions were also performed for four disaggregations of the data using all of the points, and these are shown in Table 2G. With ET* the independent variable, the regression results are essentially identical to those obtained from mean responses except for lower R^2 values.

Neutral Temperatures

The expected temperature at which a given group would vote "neutral" can also be estimated from the regression of mean ASHRAE Scale response as a function of ET*. This neutral temperature (T_n) is the temperature at which the regression line crosses the x-axis. Computationally it is obtained by taking the ratio of the y-intercept and the regression coefficient. The neutral temperatures are shown in the last column of Tables 2E through 2G. The full Thai sample produces a T_n of 25.0°C. This compares with other field studies in the tropics, notably those of Ellis (1952, 1953) in Singapore at 26.1°C and 26.7°C and Webb (1959) with 27.2°C and Rao (1952) with 26.0°C, although substantially lower than Nicol's (1974) work in Iran and India during their hot seasons which had T_n of 32.5°C and 31.1°C. Since these are all taken in unconditioned environments, perhaps a better comparison with the above is the subgroup of NV buildings whose neutral temperature is 28.5°C, placing the Thai NV result well within the tropical study range. Auliciems (1986) found the neutral temperature of air-conditioned building occupants in Northern Australia to be 24.2°C, very close to the Thai AC T_n of 24.5. Other studies done in air-conditioned buildings in temperate climates generally find lower thermal neutralities, such as Schiller's average of 22.3°C over two seasons.

Auliciems (1986) developed relations for predicting group neutrality based on either the mean indoor air temperature, mean outdoor temperature, or both, recorded over a field study. They are, respectively,

$$T_{n,i} = 5.41 + 0.73\ T_i \tag{2E}$$

$$T_{n,o} = 17.6 + 0.31\ T_o \tag{2F}$$

$$T_{n,i\&o} = 9.22 + 0.48\ T_i + 0.14\ T_o \tag{2G}$$

Results comparing group neutralities predicted by the above equations with those determined by regression are in Table 2H. For the sample as a whole, $T_{n,i}$ is the best predictor of group neutrality, coming within 0.5°C. Over the sample of disaggregated results, though, $T_{n,i\&o}$ more reliably matches the regression results, averaging within 0.7°C of the latter. Not surprisingly, mean outdoor temperature alone does not anticipate the neutral temperature of AC building occupants. $T_{n,o}$ also poorly predicts group neutrality in the hot season but improves substantially for the wet season. Here again is perhaps some evidence of seasonal acclimatization. With the hot season coming on the heels of the cool season, followed immediately by the wet season (which is hot as well as humid), extended exposure to hot outdoor weather, even for occupants of AC office buildings, could possibly cause group neutrality to increasingly reflect outdoor conditions.

Humphreys (1976) had his own empirical equation for predicting neutral temperature based on mean indoor temperature, namely,

$$T_{n,i} = 2.6 + 0.831\ T_i \qquad \text{(2H)}$$

Table 2H shows this equation to bear similar results to Auliciems' $T_{n,i}$, though with slightly lower values.

Thermal Acceptability

The concept of thermal acceptability has been widely debated in the literature but in practice is difficult to determine experimentally. The convention arrived at assumes that votes within the central three categories of the seven-point scales (i.e., from -1 to 1) connote satisfaction with the thermal environment. ASHRAE (1981) uses this criterion, along with the objective of satisfying 80% of building occupants (thermally speaking) to establish their comfort standard. The Mclnytre Scale represents an alternative method for determining thermal acceptability by assuming that any desire for change is tantamount to dissatisfaction. One can look at the interplay of the two scales by examining the cross-tabulations shown in Tables 2I and 2J for AC and NV buildings, respectively. While 52% of the respondents in AC buildings indicated "no change," a much higher 89% voted within the central three categories on the ASHRAE Scale. Similarly, only 22% wanted "no change" on the McIntyre Scale in NV buildings, but by the ASHRAE Scale thermal acceptability criteria, 58% were satisfied. Figure 2I is a relative frequency plot of the percentage of votes at "neutral" (ASHRAE = 0), at "thermal acceptability" (ASHRAE between -1 and 1), and at "no change" (McIntyre = 0), at each 0.5°C ET* bin over the range temperatures. The smooth curves are fits of these data weighted by the number of votes in each ET* bin. The "thermal acceptability" curve (by ASHRAE criteria) crosses the 80% line at roughly 22°C and 30.5°C, the latter going 4°C beyond the warm boundary of the ASHRAE summer comfort zone. The percentage of ASHRAE Scale votes strictly within the "neutral" category is much lower, at 45% or less over a broad range of ET*. Where Schiller's study showed the ASHRAE "neutral" category to be a stricter standard than the McIntyre "no change," here this is true only at ET* less than 25°C, and there is virtual consonance between them especially at temperatures above 30°C.

The ASHRAE Standard 55-81, "Thermal Environmental Conditions for Human Occupancy," depicts a summer thermal comfort "zone" bounded by loci of ET* 22.8°C to 26.1°C and dew-point temperatures of 1.7°C to 16.7°C. This thermal comfort zone is shown in Figure 2J along with bars indicating the range and mean of dew-point temperatures experienced by Thai respondents who voted within the central three ASHRAE Scale categories. Below each bar is printed the number of "acceptable" votes, and the percentage of votes these make up within each 1.0°C temperature bin. Roughly three-quarters are satisfied over a wide range of conditions, much wider in fact than the standard allows. If the "acceptable" criteria were constructed of 75% of a population voting within the central three categories (instead of 80%), the Thai thermal comfort zone would stretch from 21°C to 32°C ET*. Mean dew-point temperatures for those voting acceptable are either just under or well above the Standard 55-81 upper dew-point threshold. Other considerations besides comfort play a part in ASHRAE's choice of upper dew-point temperature boundary, health especially. Yet in view of the tremendous savings potential in relaxed comfort standards, it would be fruitful to reassess the upper dew point-boundary, along with the 80% satisfied criteria.

Correlations between Variables

Reviewed were a number of Pearson product-moment correlations among the four rating scales and among the ASHRAE Scale responses and other potential explanatory variables.

Comfort Scales. Tables 2K and 2L show correlations among the ASHRAE, McIntyre,[3] Air Flow, and Humidity scales for each season and for each of AC and NV buildings. As might be expected, there is a rather high correlation between the ASHRAE and McIntyre scales, except for the NV buildings where it drops off. Ratings on the air velocity are somewhat correlated to those on the ASHRAE and McIntyre scales in the wet season and in air-conditioned buildings. This is interesting since the air velocities are higher and more varied in NV buildings. Responses from NV buildings on the ASHRAE and McIntyre Scales are mildly correlated with perceptions of humidity levels. Other correlations are extremely weak or statistically insignificant.

ASHRAE Scale and Other Indicators. In Table 2M the correlations between responses on the ASHRAE Scale of selected subgroups to various physical and demographic factors are depicted. Indoor dry-bulb and mean radiant temperature, ET* and SET*, and vapor pressure correlate fairly well with votes on the ASHRAE Scale for both seasons. The correlations are generally lower, however, when disaggregated by space conditioning type for these same factors. Air velocity has a mixed correlation with ASHRAE for the sample subgroupings; that is, there is a weak yet significant relation between increased air velocity and *higher* ASHRAE Scale votes (counter to intuition) in the two seasons but *lower* ASHRAE Scale votes (as one would expect) in air-conditioned buildings. Air velocity is apparently unrelated to thermal sensation (as measured by the ASHRAE Scale) for NV buildings. In fact, one would expect that the conditions in NV buildings (e.g., higher and more variable airflow) would produce a stronger linkage with thermal sensation. One possible explanation for this is that among the occupants of the NV buildings studied, there were some who were accustomed to the high airflows from fans at their desks from habitual use and perhaps these respondents just incorporated high airflows into their normal thermal expectations. The negative correlation between air velocity and ASHRAE scale vote in the AC buildings is undoubtably influenced by the higher airflows coinciding with cool air emerging from supply-air diffusers. Conversely, air movement in NV buildings is usually associated with warm or hot air and may not provide much cooling sensation. Clo values are mildly negatively correlated with ASHRAE Scale votes. Other factors, such as gender, age, and expressed sensitivity to several environmental parameters, have insignificant relationships to ASHRAE Scale responses.

Respondents were asked to indicate the level of use of home air-conditioning, whether they never used it (coded 0), seldom (1), usually (2), or always (3). This question was intended as a rough proxy for indicating the thermal context of the respondent's time away from the office. Their answers produced no simple direct correlation with their responses on the ASHRAE Scale as shown in Table 2M. But because responses to the ASHRAE Scale should reflect a combination of the state of the *immediate* thermal environment as well as that to which

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[3] For the purpose of interpreting the signs in the McIntyre Scale, a response of "cooler" is coded as -1, "warmer" as 1, and "no change" as 0.

the respondent is normally accustomed, the differences of the office thermal environment were factored out by binning responses by ET*. Table 2N shows the correlation between home air-conditioning and ASHRAE votes binned by 1°C ET*. The correlations are generally insignificant with the exception of a few ET* bins, and for those the correlations are not particularly strong. Obviously it would be more informative to have a more quantitative description of the domestic thermal environment than our rather imperfect indicator.

Probit Analysis

Probit analysis (Finney 1971) is a technique whereby data are sorted into two categories: those that possess some quality and those that do not, often at different levels (or bins) of some explanatory variable. These binary sets are transformed into percentages within each explanatory variable bin. The resulting percentages can also be thought of as relative frequencies within each bin. These relative frequencies done over the range of bins is, in effect, a cumulative relative frequency distribution. The technique was originally developed for use in analyzing the effectiveness of pesticides. In that particular case, the binary sets were percentage of insect kills versus non-kills at different insecticide dose levels. Probit analysis has been used to evaluate thermal comfort responses on rating scales as a function of temperature (Ballantyne 1977; Humphreys 1976). The binary sets are percentages of votes greater than or equal to--versus less than--a given vote category. A family of curves results when done over the range of comfort scale categories. For example, using the ASHRAE Scale, one binary grouping would be the percentage of the votes equal to or greater than "neutral" and those less than "neutral," done at 0.5°C ET* intervals. The result is a set of curves, each depicting the transition to higher voting categories. This technique tells one the temperatures at which the majority of the sample population would change their votes from one category to the next (i.e., the transition temperatures) as well as the category widths of the scales in question. The chief feature of probit analysis is that it circumvents the assumption of equal scale category widths embedded in regression analysis.

Figures 2K and 2L show probit analysis of ASHRAE and McIntyre Scale votes, respectively, for the Thai data binned by ET*. The number of curves is always the number of categories minus one, so in Figure 11 there are six curves and in Figure 12 just two. For reasons of visual clarity, only the curves (and not the actual data points) have been plotted in Figure 2K. The transition temperature is a value often quoted in the literature and is defined as that temperature at which the majority (i.e., 50% or more) of the respondents would change their votes to the next higher category. In the ideal case, a sufficient temperature range would allow the plotting of each curve from 0 to 100% of the votes. However, in this study only three of the six curves of the ASHRAE Scale probit analysis pass across the 50% line allowing determination of transition temperatures. The transition from "slightly cool" (-1) to "neutral" (0) takes place at approximately 22.5°C; from "neutral" to "slightly warm" (1) at 27.5°C; and from "slightly warm" to "warm" (2) at 33.5°C. These transition temperatures imply category widths of 5°C and 6°C, respectively, for the "neutral" and "slightly warm" categories. The ASHRAE Scale categories from the Thai sample are considerably wider as compared to those of McIntyre (1980), who used a large data set collected at a state university and found corresponding transition temperatures of 3.8°C and 3.1°C, respectively. Ballantyne (1977) presented results of a study of Melanesians in Papua New Guinea and found the transition temperature from "cool" to "neutral" to fall at 24.4°C and from "neutral" to "warm" at 30.0°C, implying an even wider 5.6°C central category width.[4]

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[4] Note that Ballantyne employed at five-point scale instead of the usual seven-point scale. Other studies have shown that scales using fewer points have wider categories. This makes the Thai results surprisingly close to those using subjects in a similar climate yet with a "broader" scale.

On the McIntyre Scale, only the transition temperature from "no change" to "cooler" is defined, and it is about 25.5°C. It is not possible to determine any category width for the McIntyre scale with these data.

It is interesting to note that the point at which 20% of the Thai respondents changed their votes from one or below to higher than one (i.e., 80% retained their choice) is 30.5°C, identical to the earlier finding of the upper bound of thermal acceptability. In fact, Figure 2K is useful for determining the Thai comfort zone under different criteria of "thermal acceptability." For instance, suppose the transition temperature were used as the criteria (i.e., 50% shifting their votes). The rightmost boundary of the comfort zone would slide over to 33.5°C ET*!

Other Comfort Indices

In the results reported so far we have used Effective Temperature (ET*) for combining the thermal effects of the four environmental variables--temperature, radiant temperature, humidity, and air velocity--into a single index. Other comfort indices exist, however, and in this section distinctions between some of the more widely used indices and their relative merits in the Thai context are explored.

Rational Indices. The Standard Effective Temperature (SET*) is an extension of ET* in that it also normalizes for the two personal variables, clothing insulation and metabolic rate. Standard clothing insulation values are based on metabolic rate. Thus, SET* is defined as the value of an isothermal enclosure with radiant temperature equal to the air temperature, at 50% relative humidity, and air-velocity of 0.1 m/s, in which a person with standard clothing for the actual activity level would have the same heat loss at the same mean skin temperature and the same skin wettedness as he or she does in the actual environment with the actual clothing insulation after one hour of exposure. Like ET*, SET* is an index based on analysis of the thermoregulatory response of the body to thermal stress, which is represented in a two-node heat transfer model (Gagge et al. 1972). The key physiological determinants of human comfort used in the model are skin temperature in cooler than neutral exposures and skin wettedness in warmer than neutral exposures. Skin wettedness is the fraction of the skin surface covered with sweat and is related to the ability of the body to lose heat through evaporation in the given environment. Numerous experiments in warm, humid environments have confirmed a strong relationship between skin wettedness and thermal discomfort. TSENS is a comfort index calculated with the J.B. Pierce model analogous to, and used for, predicting votes on the ASHRAE seven-point scale. TSENS is based on the mean body temperature, which, in turn, is related to skin wettedness when body temperature is regulated by sweating (Doherty and Arens 1988).

Fanger (1970), the pioneer in developing rational methods for predicting thermal comfort responses, produced two linked indices with his Comfort Equation: Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Fanger's central premise is that thermal sensation relates to the state of the body rather than the environment. The original Comfort Equation he devised performed a heat balance between the body and the environment, coupled with two key empirical observations: that both the skin temperature and evaporative heat loss *at comfort* are linearly proportional to metabolic rate. PMV is an expression of the difference between the actual metabolic rate and that required to maintain "comfort" as determined by the heat balance calculation. PMV is essentially a rational prediction of the population mean vote on the ASHRAE seven-point scale (same as used in this study). PPD is derived from the the distribution of votes from thermal comfort laboratory experiments as a function of temperature that were related to PMV and the ASHRAE acceptability criteria (that votes outside the central three categories are votes of dissatisfaction).

A criticism of Fanger's method is that the results become increasingly inaccurate at conditions away from comfort, e.g., at high temperatures, humidities, or metabolic rates, and further, that the data upon which it is based come from a fairly homogeneous group of white, collegeaged subjects whose responses may not be representative in all possible contexts.

The mean PMV and mean TSENS are plotted with the mean ASHRAE Scale vote from the sample of Thai office workers as a function of ET* in Figure 2M and SET* in Figure 2N. TSENS overpredicts the average Thai ASHRAE vote below 24°C ET* but is generally within 0.5 Scale units in warmer conditions. Surprisingly, PMV is within 0.5 scale units of average Thai ASHRAE votes over most of the range and *underpredicting* it below 33°C ET*. When plotted versus SET* (Figure 2N), all of the curves smooth out. TSENS and the average ASHRAE vote show remarkable agreement over the range, much more so than with ET*. PMV, on the other hand, diverges from the average ASHRAE vote below 25°C SET* by over one scale unit. PMV, TSENS, and the Thai votes agree quite well above 28°C SET*. This suggests that either the Gagge or Fanger models can be used to predict the average Thai office worker response in NV buildings. Thus, while Fanger's method is theoretically lacking in relatively extreme situations away from comfort, in the Thai context it is apparently vindicated. For Thai AC environments, however, the Gagge model is preferred.

Figure 2O compares the percent dissatisfied (those voting *outside* the central three ASHRAE scale categories) of the Thai sample and the PPD calculated using the Fanger model. These are plotted as a function of the average ASHRAE scale vote. Each PPD point represents the average of all the PPDs calculated for each individual *within a given 0.5°C ET* bin*. Similarly, the percent dissatisfied from the Thai data are taken from ET* bins. For each series we show a second-order polynomial fit to the data weighted by the number of data points behind each plotted point. The y-axis scale is logarithmic to facilitate comparison with Fanger's (1970) classic PPD versus PMV plot also using this format. The PPD fit grossly overpredicts Thai dissatisfaction below thermal neutrality by as much as 25% but is quite accurate in the region above about 0.3 on the ASHRAE scale. Figure 2O is consistent with Figure 2M, and this is to be expected since PPD and PMV are linked. One final point worth noting is that the minimum point in the percent dissatisfied curve occurs slightly below the zero scale point. It has been suggested that people accustomed to a hot climate might find a slightly cool environment preferable to a neutral one. To the extent that minimal dissatisfaction connotes "preference," the small offset of the curve may demonstrate this effect on the part of the Thai sample.

Empirical Indices. Field studies performed in the tropics have yielded numerous empirical indices for predicting the response to thermal conditions. Most of these empirical indices are simple to compute using commonly measured variables. A disadvantage of this class of comfort index is that the applicability of the index is limited to the conditions found in the data set from which the index is derived. For field studies, where the researcher exercises little or no control over the environmental conditions (the usual case), the range of applicability can be rather narrow. Comparisons of empirical indices applied to the Thai data set are beyond the scope of this chapter.

CONCLUSIONS

A sample of thermal comfort responses and environmental data was collected for 1146 Thai office workers. Preliminary findings from analyzing two seasons of data gathered in four Bangkok buildings are as follows:

- There is little apparent gender or seasonal bias in the responses, although different clothing insulation between men and women could be masking real differences, and the weather differences between the hot and wet seasons in Bangkok in 1988 were more subtle than usual.

- Two distinct populations emerged from our analysis: those who worked in air-conditioned offices and those who worked in naturally ventilated offices. The latter group expressed satisfaction with temperatures and humidities well above those deemed acceptable in the HVAC industry.
- Regression of the mean ASHRAE Scale responses produced a rather shallow slope term indicating less sensitivity on the part of the Thais to thermal environment change relative to other populations studied in the literature. This finding is also supported by an analysis showing the ASHRAE Scale category widths to be substantially wider than other studies have found using the seven-point scale.
- The Thai neutral temperature of 25°C is in agreement with other field studies done in the tropics but above most from temperate climates.
- This sample registered thermal acceptability (as defined by ASHRAE Standard 55-81) over a broader effective temperature range than previous work, from 22°C to 30.5°C. This extends the hot and humid boundary of the summer comfort zone 4°C outward. The implications of this finding, if put into practice, could have profound impact on energy use in commercial buildings located in the tropics. Relaxing the criteria for defining the comfort zone boundaries (on the humidity or temperature "edges") even slightly from the present choice could push the savings significantly further.
- Gagge's TSENS model predicts the average Thai thermal sensation well over the range of temperatures experienced in this study. Fanger's PMV does less well at lower temperatures but at temperatures above 28°C is quite accurate.

Table 2A.
Distribution of Physical Data
Hot Season Study

Building*	D	M	P	S	T	All
Sample Size	99	97	25	195	196	600
Clothing (clo)						
average	.49	.50	.50	.55	.56	.53
std dev	.09	.09	.10	.12	.12	.12
min	.24	.28	.24	.25	.24	.24
max	.72	.68	.65	.89	.95	.95
Air Temperature (^{o}C)						
average	30.0	32.6	30.2	23.2	24.0	26.3
std dev	1.5	0.8	1.5	1.1	1.4	4.0
min	25.9	31.4	24.0	19.5	19.7	19.5
max	32.1	34.1	31.3	25.8	26.5	34.1
Vapor Pressure (Torr)						
average	24.1	24.8	23.7	12.2	13.4	17.1
std dev	1.1	0.8	4.0	2.9	1.1	5.9
min	18.9	23.1	9.1	6.9	11.4	6.9
max	26.4	26.2	26.3	16.6	15.7	26.4
Air Velocity (m/sec)						
average	0.33	0.31	0.26	0.13	0.12	.20
std dev	0.26	0.18	0.21	0.03	0.02	.16
min	0.11	0.12	0.10	0.09	0.09	.09
max	1.68	1.20	0.83	0.31	0.19	1.68
ET* (^{o}C)						
average	32.3	34.6	32.6	24.1	24.9	27.8
std dev	1.5	0.5	2.0	1.1	1.4	4.5
min	28.5	33.5	25.5	20.5	20.7	20.5
max	34.3	36.0	34.0	27.3	27.5	36.0

* Buildings D, M, and P are naturally-ventilated while S and T are air-conditioned.

Table 2B.
Distribution of Physical Data
Wet Season Study

Building*		D	M	S	T	All
Sample Size		95	73	181	197	546
Clothing (clo)						
	average	.50	.46	.55	.57	.53
	std dev	.10	.11	.11	.11	.12
	min	.27	.24	.27	.31	.24
	max	.71	.65	.91	1.19	1.19
Air Temperature (°C)						
	average	30.6	30.5	22.7	24.6	25.8
	std dev	1.3	1.2	1.0	.95	3.4
	min	28.3	28.1	20.5	22.7	20.5
	max	34.2	32.4	25.3	26.9	34.2
Vapor Pressure (Torr)						
	average	24.5	24.1	12.0	14.2	16.6
	std dev	.9	.9	2.3	.7	5.4
	min	22.5	22.1	7.0	12.7	7.0
	max	27.9	28.4	16.7	18.0	28.4
Air Velocity (m/sec)						
	average	.35	.32	.13	.12	.19
	std dev	.38	.22	.02	.02	.21
	min	.09	.11	.09	.09	.09
	max	2.25	1.63	.25	.20	2.25
ET* (°C)						
	average	32.9	32.6	23.5	25.4	27.0
	std dev	1.0	1.1	1.0	1.0	4.0
	min	30.7	30.1	21.2	23.5	21.2
	max	35.5	34.6	26.0	28.2	35.5

* Buildings D and M are naturally-ventilated while S and T are air-conditioned.

Table 2C.
Crosstabulation of ET* vs. ASHRAE Scale
All Buildings (Two Seasons)

	% ASHRAE Scale Thermal Sensation Votes[1,2]														
ET*	-3	-2.5	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	2.5	3	Row Totals	
20.5	0	0	0	0	0	0	50	0	50	0	0	0	0	.2	(2)
21	0	0	50	0	50	0	0	0	0	0	0	0	0	.2	(2)
21.5	0	10	10	10	40	0	30	0	0	0	0	0	0	.9	(10)
22	0	0	23.8	0	38.1	4.8	33.3	0	0	0	0	0	0	1.8	(21)
22.5	5.8	0	7.2	1.4	42.0	4.3	36.2	0	1.4	0	1.4	0	0	6.0	(69)
23	2.2	1.1	12	1.1	38.0	3.3	35.9	0	4.3	0	2.2	0	0	8.0	(92)
23.5	0	0	3.4	1.1	33.7	1.1	46.1	1.1	10.1	0	1.1	0	2.2	7.8	(89)
24	0	0	5.2	0	19.6	3.1	50.5	1.0	17.5	0	2.1	0	1.0	8.5	(97)
24.5	0	0	2.9	1	27.2	1.9	42.7	2.9	19.4	0	1.9	0	0	9.0	(103)
25	0	0	1.2	0	15.1	2.3	44.2	1.2	26.7	0	8.1	0	1.2	7.5	(86)
25.5	0	0	1.4	1.4	16.7	1.4	36.1	1.4	36.1	1.4	4.2	0	0	6.3	(72)
26	0	0	0	0	19.6	1.8	32.1	3.6	39.3	0	1.8	0	1.8	4.9	(56)
26.5	0	0	0	0	3.2	0	38.7	3.2	38.7	0	12.9	0	3.2	2.7	(31)
27	0	0	0	0	0	0	42.9	0	47.6	0	9.5	0	0	1.9	(22)
27.5	0	0	0	0	0	0	16.7	0	50	0	33.3	0	0	.5	(6)
28	0	0	0	0	0	0	0	0	0	0	100	0	0	.3	(3)
28.5	0	0	0	0	33.3	0	66.7	0	0	0	0	0	0	.3	(3)
29	0	0	0	0	0	0	100	0	0	0	0	0	0	.2	(2)
29.5	0	0	0	0	50	0	0	0	0	0	50	0	0	.3	(4)
30	0	0	0	0	0	0	66.7	0	33.3	0	0	0	0	.3	(3)
30.5	0	0	0	0	0	0	41.7	0	33.3	8.3	8.3	8.3	0	1.0	(12)
31	0	0	0	0	0	0	31.3	0	43.8	0	25	0	0	1.4	(16)
31.5	0	0	0	0	3.1	0	37.5	0	40.6	0	15.6	0	3.1	2.8	(32)
32	0	0	0	0	2.2	0	33.3	2.2	33.3	0	24.4	2.2	2.2	3.9	(45)
32.5	0	0	0	0	0	0	20.4	0	38.9	0	33.3	1.9	5.6	4.7	(54)
33	0	0	0	0	2.1	0	22.9	0	31.3	0	31.3	4.2	8.3	4.2	(48)
33.5	0	0	0	0	1.8	0	15.8	3.5	29.8	3.5	35.1	0	10.5	5	(57)
34	0	0	0	0	0	0	7.9	2.6	36.8	2.6	34.2	2.6	13.2	3.3	(38)
34.5	0	0	0	0	0	0	6.4	0	25.5	0	40.4	4.3	23.4	4.1	(47)
35	0	0	0	0	0	0	0	0	23.5	11.8	29.4	17.6	17.6	1.5	(17)
35.5	0	0	0	0	0	0	0	0	16.7	16.7	66.7	0	0	.5	(6)
36	0	0	0	0	0	0	0	0	0	0	0	0	100	.1	(1)
Column Totals	.5 (6)	.2 (2)	3.1 (36)	.5 (6)	17.3 (198)	1.5 (17)	33.9 (389)	1.2 (14)	23.8 (273)	.7 (8)	12.7 (145)	1.0 (11)	3.6 (41)	100	(1146)

1 Percentages are calculated by row, e.g. within each ET* category.
2 Numbers in parentheses are the total number of votes in the respective column or row.

Table 2D.
Crosstabulation of ET* vs. McIntyre Scale
All Buildings (Two Seasons)

	% McIntyre Scale Votes[1,2,3]				
ET*	"Cooler"	"No Change"	"Warmer"	Row Totals	
20.5	50	50	0	.2	(2)
21	0	50	50	.2	(2)
21.5	10.0	70.0	20.0	.9	(10)
22	4.8	81.0	14.3	1.8	(21)
22.5	17.4	62.3	20.3	6.0	(69)
23	19.6	62.0	18.5	8.0	(92)
23.5	30.3	62.9	6.7	7.8	(89)
24	38.1	52.6	9.3	8.5	(97)
24.5	35.0	57.3	7.8	9.0	(103)
25	52.3	45.3	2.3	7.5	(86)
25.5	59.7	34.7	5.6	6.3	(72)
26	53.6	42.9	3.6	4.9	(56)
26.5	77.4	22.6	0	2.7	(31)
27	59.1	40.9	0	1.9	(22)
27.5	100	0	0	.5	(6)
28	66.7	33.3	0	.3	(3)
28.5	0	100	0	.3	(3)
29	100	0	0	.2	(2)
29.5	50	50	0	.3	(4)
30	66.7	33.3	0	.3	(3)
30.5	50	50	0	1.0	(12)
31	75	25	0	1.4	(16)
31.5	62.5	34.4	3.1	2.8	(32)
32	75.6	22.2	2.2	3.9	(45)
32.5	70.4	25.9	3.7	4.7	(54)
33	83.3	14.6	2.1	4.2	(48)
33.5	86	14	0	5.0	(57)
34	84.2	7.9	7.9	3.3	(38)
34.5	85.1	14.9	0	4.1	(47)
35	94.1	5.9	0	1.5	(17)
35.5	83.3	16.7	0	.5	(6)
36	100	0	0	.1	(1)
Column Totals	51.9 (595)	41.4 (475)	6.6 (76)	100	(1146)

1 McIntyre Scale indicates responses to the question, "I would like to be ...."
2 Percentages are calculated by row, e.g. within each ET* category.
3 Numbers in parentheses are the total number of votes in the respective column or row.

Table 2E.
Regression of *Mean* ASHRAE Scale responses and ET*

	Slope	Intercept	R^2	Nr. Pts.	T_n (°C)
All	0.176	-4.406	.91	32	25.0
Hot Season	0.187	-4.586	.91	16	24.5
Wet Season	0.154	-3.959	.85	32	25.7
Air-Conditioned	0.324	-7.952	.88	26	24.5
Nat.-Ventilated	0.289	-8.247	.87	17	28.5
Men	0.175	-4.313	.84	28	24.6
Women	0.179	-4.553	.90	32	25.4
Hot Sea., Men	0.181	-4.391	.84	27	24.3
Hot Sea., Women	0.192	-4.743	.88	31	24.7
Wet Sea., Men	0.164	-4.111	.73	23	25.1
Wet Sea., Women	0.153	-4.032	.88	25	26.4
Hot Sea., AC	0.235	-5.746	.80	21	24.5
Hot Sea., NV	0.237	-6.321	.69	19	26.7
Wet Sea., AC	0.329	-8.185	.88	15	24.9
Wet Sea., NV	0.157	-4.147	.63	12	26.4
Hot, Men, AC	0.200	-4.847	.58	18	24.2
Hot, Men, NV	0.224	-5.858	.61	15	26.2
Hot, Women, AC	0.264	-6.475	.77	18	24.5
Hot, Women, NV	0.246	-6.627	.58	18	26.9
Wet, Men, AC	0.324	-8.004	.77	14	24.7
Wet, Men, NV	0.157	-4.006	.17	10	25.5
Wet, Women, AC	0.322	-8.061	.83	14	25.0
Wet, Women, NV	0.170	-4.627	.71	11	27.2

Table 2F.
Regression of *Mean* ASHRAE Scale responses and SET*

	Slope	Intercept	R^2	Nr. Pts.	T_n (°C)
Hot Season	0.194	-4.632	.92	33	23.9
Wet Season	0.157	-3.932	.84	33	25.0
Air-Conditioned	0.171	-4.178	.71	22	24.4
Nat.-Ventilated	0.161	-3.787	.70	21	23.5

Table 2G.
Regression of *All* ASHRAE Scale responses and ET*

	Slope	Intercept	R^2	Nr. Pts.	T_n (°C)
Hot Season	0.187	-4.636	.48	599	24.8
Wet Season	0.154	-4.001	.32	545	26.0
Air-Conditioned	0.326	-8.090	.20	756	24.8
Nat.-Ventilated	0.289	-8.298	.19	363	28.7

Table 2H.
Comparison of Neutral Temperatures (T_n)*

			Regression	Auliciems			Humphreys
	T_i	T_o	T_n	$T_{n,i}$	$T_{n,o}$	$T_{n,i\&o}$	$T_{n,i}$
All	26.1	29.9	25.0	24.5 (-.5)	26.9 (1.9)	25.9 (.9)	24.3 (-.7)
Hot Season	26.3	30.7	24.5	24.6 (.1)	27.1 (2.6)	26.1 (1.6)	24.5 (0)
Wet Season	25.8	29.1	25.7	24.2 (-1.5)	26.6 (.9)	25.7 (0)	24.0 (-1.7)
Air-Conditioned	23.6	30.5	24.5	22.6 (-1.9)	27.1 (2.6)	24.8 (.3)	22.2 (-2.3)
Nat.-Ventilated	30.9	28.7	28.5	28.0 (-.5)	26.5 (-2.0)	28.1 (-.4)	28.3 (-.2)
Men	25.4	30.1	24.6	24.0 (-.6)	26.9 (2.3)	25.6 (1.0)	23.7 (-.9)
Women	26.5	29.8	25.4	24.8 (-.6)	26.8 (1.4)	26.1 (.7)	24.6 (-.8)

* Numbers in parentheses are the differences between the neutral temperatures using regression and given equation.

Table 2I.
Crosstabulation of ASHRAE Scale vs. McIntyre Scale
Air-Conditioned Buildings (All Seasons)

ASHRAE	% McIntyre Scale Votes[1,2,3]				
Scale	"Cooler"	"No Change"	"Warmer"	Row Totals	
-3	0	0	100	.8	(6)
-2.5	0	0	100	.3	(2)
-2	5.6	38.9	55.6	4.8	(36)
-1.5	0	50	50	.8	(6)
-1	7.9	74.9	17.3	25.2	(191)
-0.5	29.4	64.7	5.9	2.2	(17)
0	29.1	70.3	.7	40.4	(306)
0.5	90	10	0	1.3	(10)
1	94.6	4.7	.7	19.6	(148)
1.5	100	0	0	.1	(1)
2	96.4	3.6	0	3.7	(28)
2.5	0	0	0	0	(0)
3	100	0	0	.8	(6)
Column Totals	38.8 (294)	52.2 (395)	9 (68)	100	(757)

1 McIntyre Scale indicates responses to the question, "I would like to be ......"
2 Percentages are calculated by row, e.g. within each ASHRAE Scale category.
3 Numbers in parentheses are the total number of votes in the respective column or row.

Table 2J.
Crosstabulation of ASHRAE Scale vs. McIntyre Scale Naturally-Ventilated Buildings (All Seasons)

ASHRAE Scale	% McIntyre Scale Votes			Row Totals	
	"Cooler"	"No Change"	"Warmer"		
-3	0	0	0	0	(0)
-2.5	0	0	0	0	(0)
-2	0	0	0	0	(0)
-1.5	0	0	0	0	(0)
-1	0	66.7	33.3	1.6	(6)
-0.5	0	0	0	0	(0)
0	40	60	0	22	(80)
0.5	100	0	0	.3	(1)
1	78.9	18.7	2.4	33.8	(123)
1.5	80	0	20	1.4	(5)
2	94.5	3.6	1.8	30.2	(110)
2.5	100	0	0	1.9	(7)
3	100	0	0	8.8	(32)
Column Totals	76.1 (277)	21.7 (79)	2.2 (8)	100	(364)

Table 2K.
Simple Correlations between Comfort Scales

Naturally-Ventilated → ↓ Air-Conditioned	ASHRAE Scale	McIntyre Scale	Air Flow Scale	Humidity Scale
ASHRAE Scale		-.47***	-.12*	-.21***
McIntyre Scale	-.69***		.14**	.21***
Air Flow Scale	-.25***	.23***		.13*
Humidity Scale	-.09*	.07*	.19***	

Table 2L.
Simple Correlations between Comfort Scales

Wet Season → ↓ Hot Season	ASHRAE Scale	McIntyre Scale	Air Flow Scale	Humidity Scale
ASHRAE Scale		-.67***	-.25**	.02
McIntyre Scale	-.67***		.23***	.05
Air Flow Scale	-.10*	.12**		.10*
Humidity Scale	-.13***	.09*	.21***	

"*" = significant beyond .05; "**" = significant beyond .01; "***" = significant beyond .001.

Table 2M.
Simple Correlations between ASHRAE Scale and various Indices

	Hot Season	Wet Season	Air-Conditioned	Naturally-Ventilated
Outdoor Temperature	.70***	.58***	.44***	.44***
Mean Radiant Temperature	.69***	.57***	.42***	.42***
Vapor Pressure	.65***	.51***	.26***	.14**
Air Velocity	.33***	.19***	-.13***	-.06
Clo	-.27***	-.20***	-.16***	.02
ET*	.69***	.56***	.45***	.43***
SET*	.66***	.53***	.29***	.34***
Gender	.08*	-.03	-.09*	-.05
Age	.13*	.16***	.03	.09
Use of Home AC	-.06	-.02	.06	.07
Temperature Sensitivity	.03	-.03	-.01	.08
Humidity Sensitivity	.02	0	-.02	-.05
Air Flow Sensitivity	.01	-.03	.02	-.04

* Significant beyond .05
** Significant beyond .01
*** Significant beyond .001

Table 2N.
Correlation between ASHRAE Scale and Use of Home AC
(binned by ET*)

ET*	Correlation	Significance	Nr. Points
21	.26	.742	4
22	.40	.024	31
23	.02	.755	161
24	-.04	.595	186
25	.20	.005	189
26	.06	.491	128
27	-.01	.953	53
28	.24	.540	9
29	.41	.495	5
30	-.50	.257	7
31	-.12	.553	28
32	.20	.076	77
33	.19	.062	102
34	-.14	.172	95
35	.11	.402	64
36	.36	.426	7

Figure 2A.
Data Acquisition System for Physical Measurements

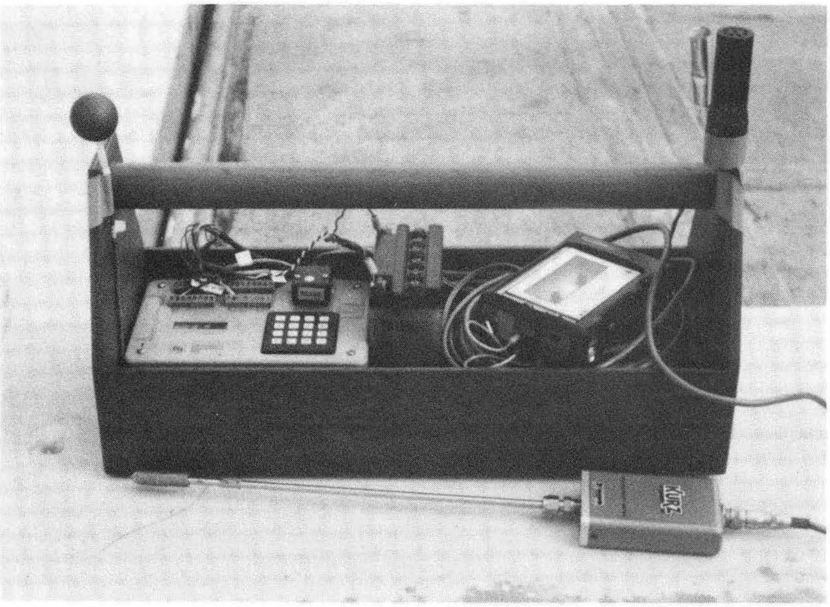


Figure 2B.
Subjective Rating Scales

ASHRAE Scale: "Rate how you feel at this moment"

-3	-2	-1	0	1	2	3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

McIntyre Scale: "I would like to be ..."

Warmer
No Change
Cooler

Humidity Scale: "Rate the immediate environment at this moment in terms of humidity"

-3	-2	-1	0	1	2	3
much too dry	too dry	slightly dry	just right	slightly humid	too humid	much too humid

Air Flow Scale: "Rate the immediate environment at this moment in terms of air movement"

-3	-2	-1	0	1	2	3
much too still	too still	slightly still	just right	slightly breezy	too breezy	much too breezy

Figure 2C.
Age Frequency Distribution

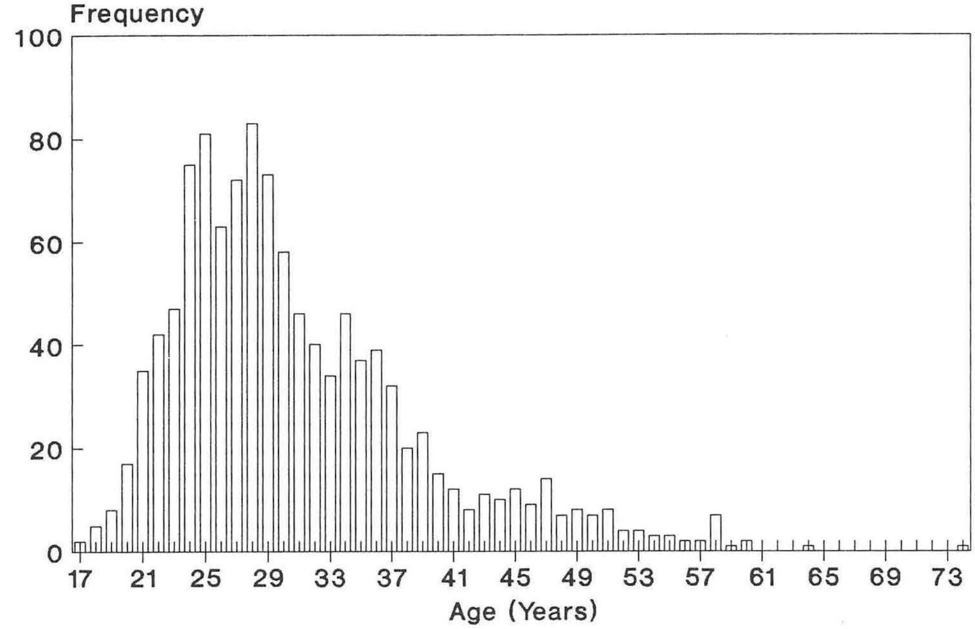


Figure 2D.
Clo Value Frequency by Gender

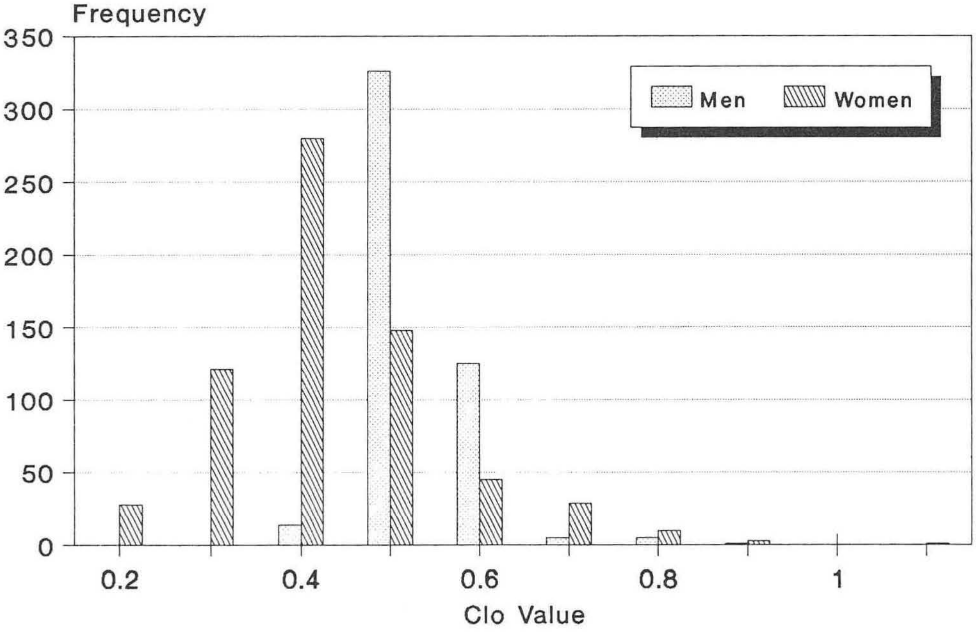


Figure 2E.
ET* Frequencies by Season

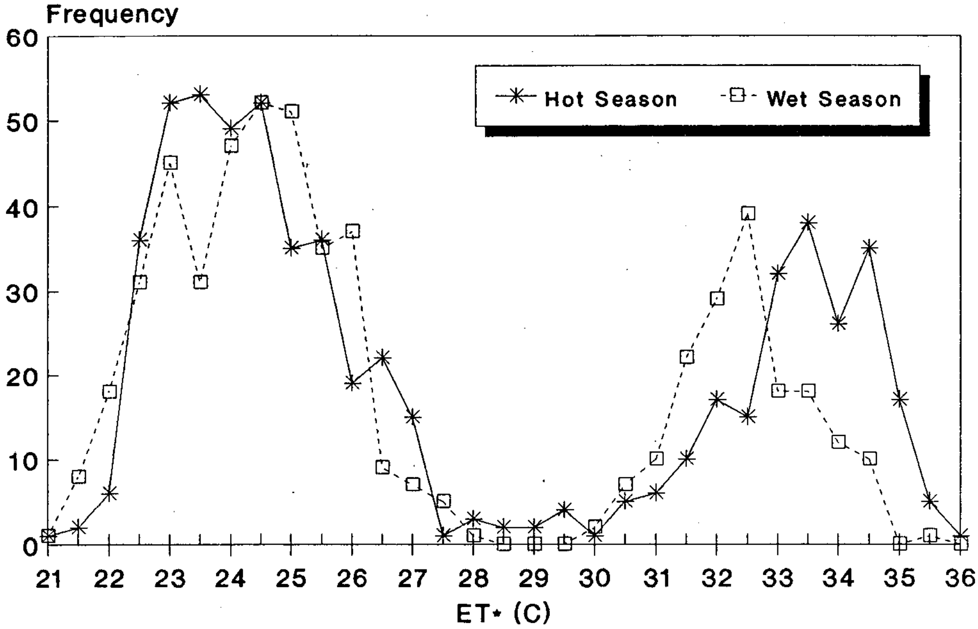


Figure 2F.
Relative Frequency of ASHRAE Votes

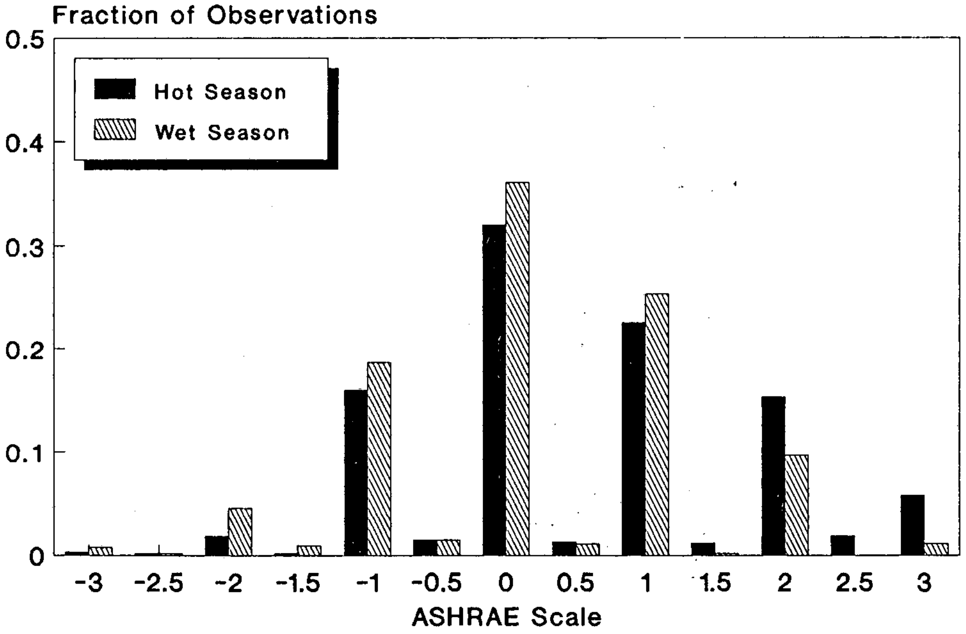


Figure 2G.
Relative Frequency of ASHRAE Votes

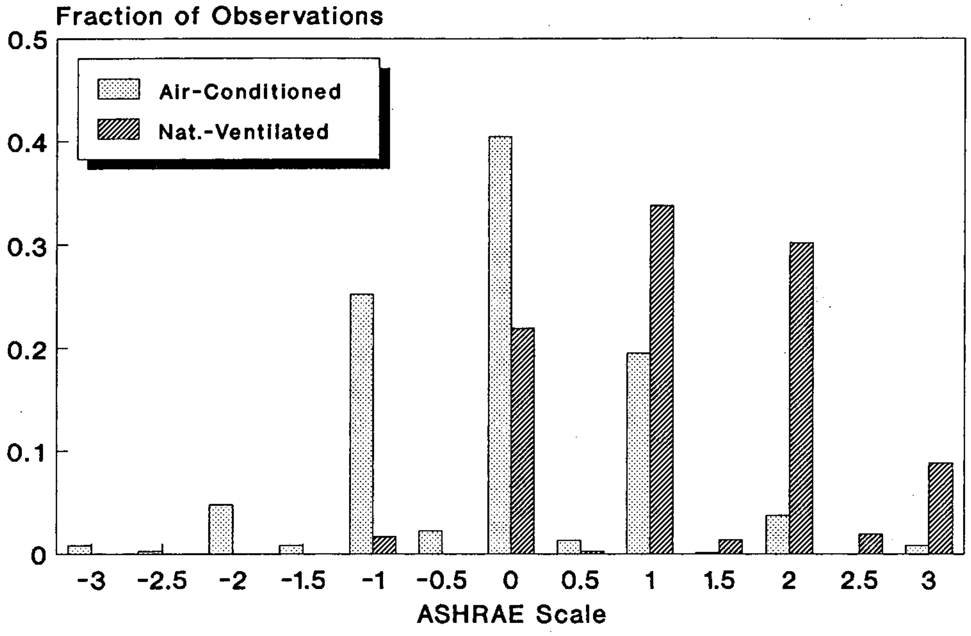


Figure 2H.
Relative Frequencies of McIntyre Votes

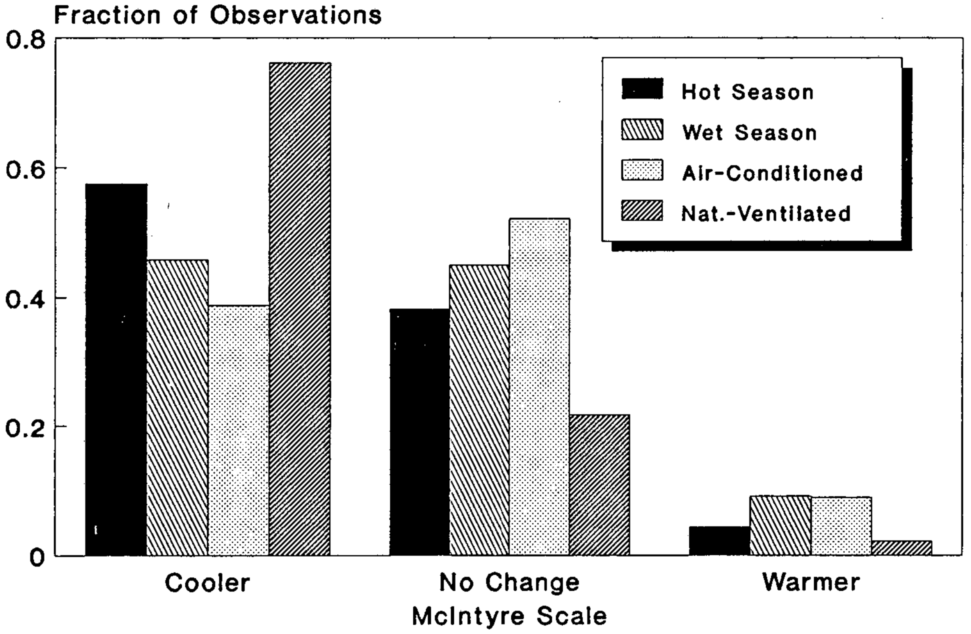


Figure 2I.
Thermal Acceptability

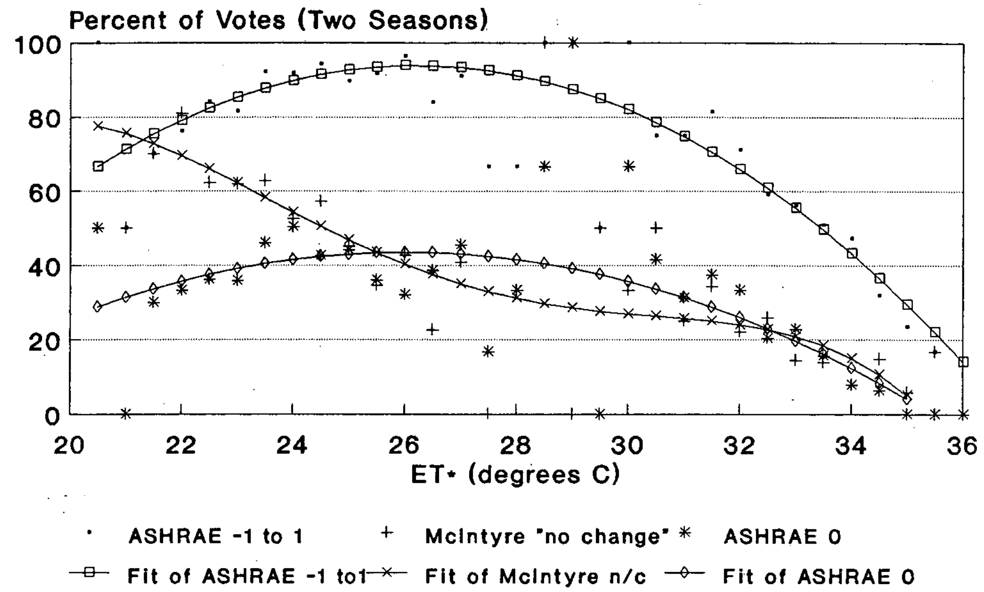


Figure 2J.
"Acceptable" Votes vs. ASHRAE Standard

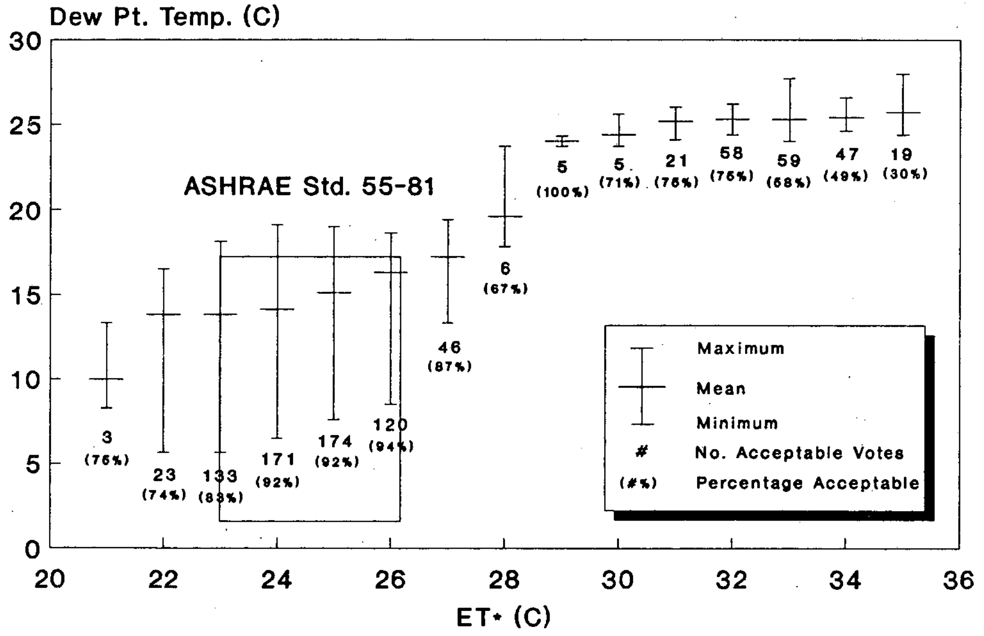


Figure 2K.
Probit Analysis of ASHRAE Scale Votes

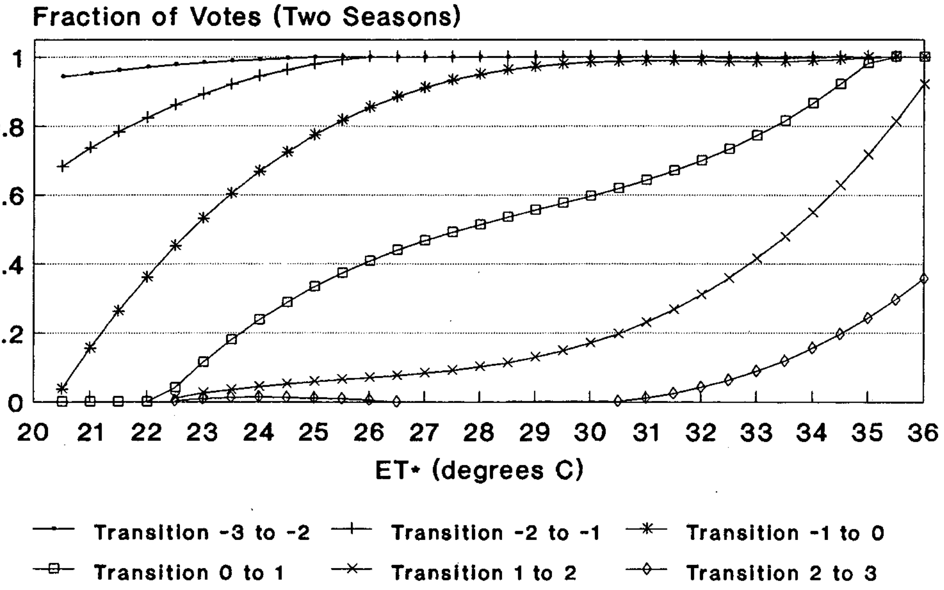


Figure 2L.
Probit Analysis of McIntyre Scale Votes

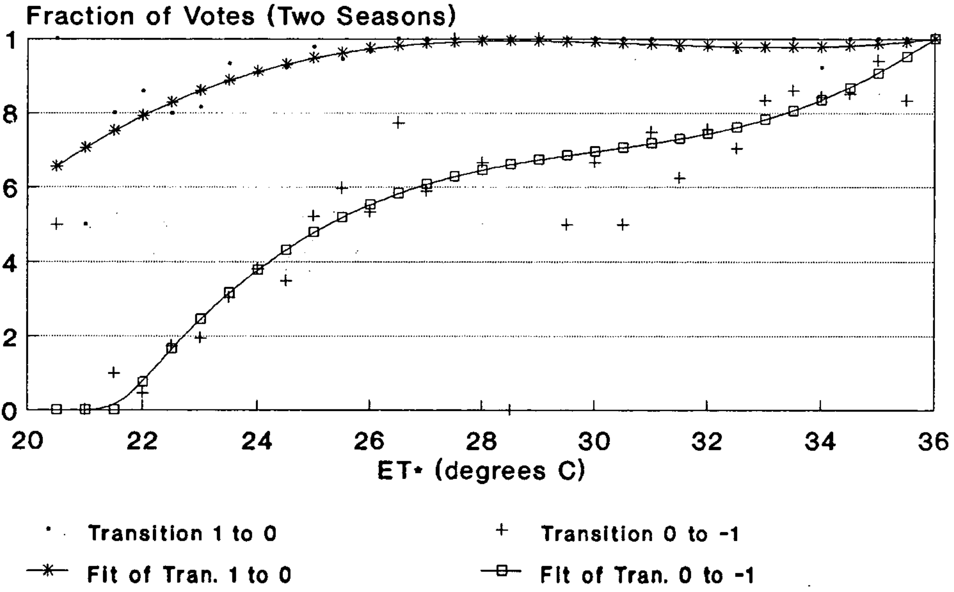


Figure 2M.
ASHRAE Vote, TSENS, and PMV vs. ET*

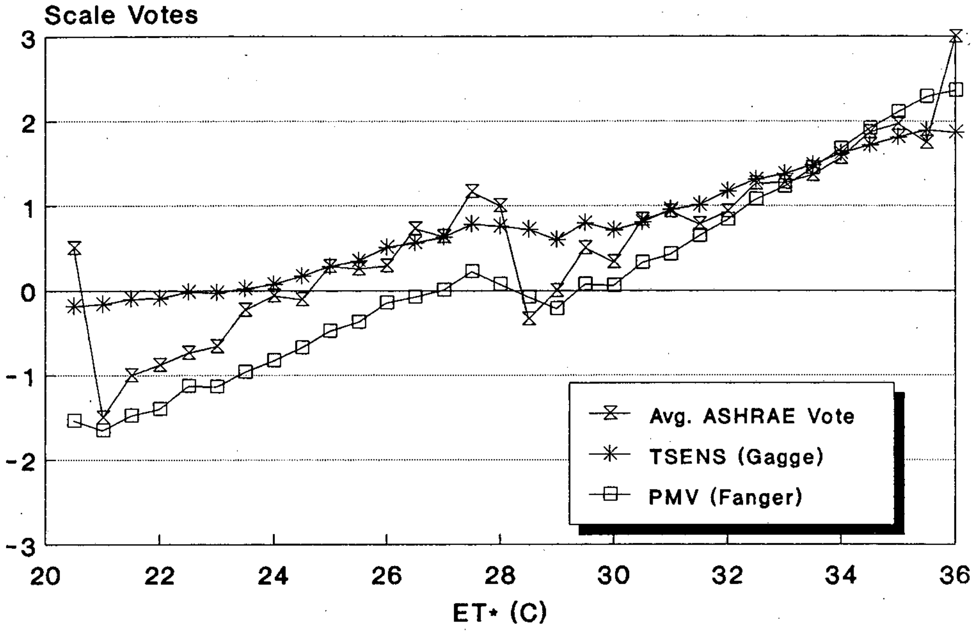


Figure 2N.
ASHRAE Vote, TSENS, and PMV vs. SET*

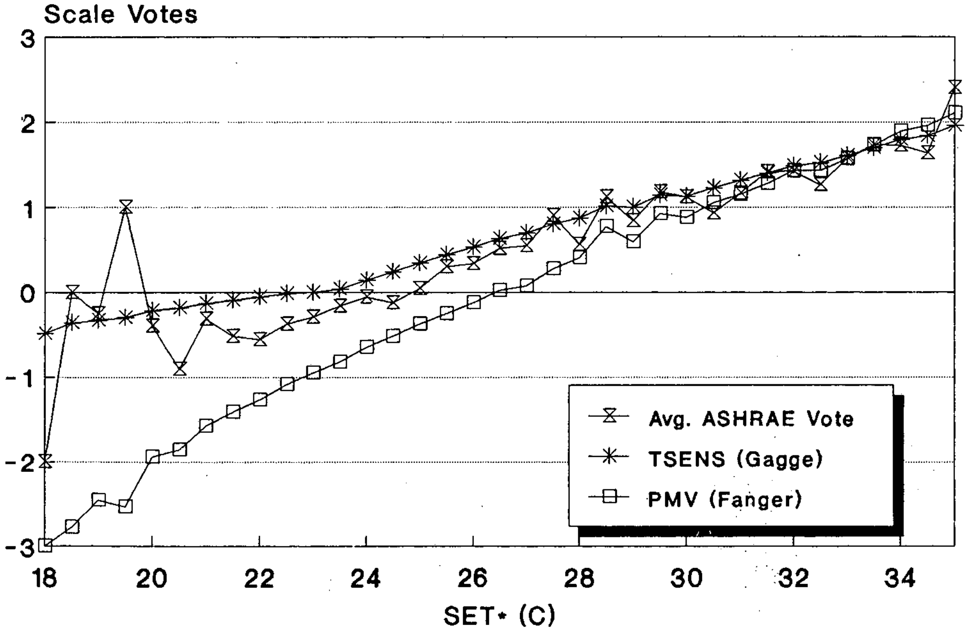
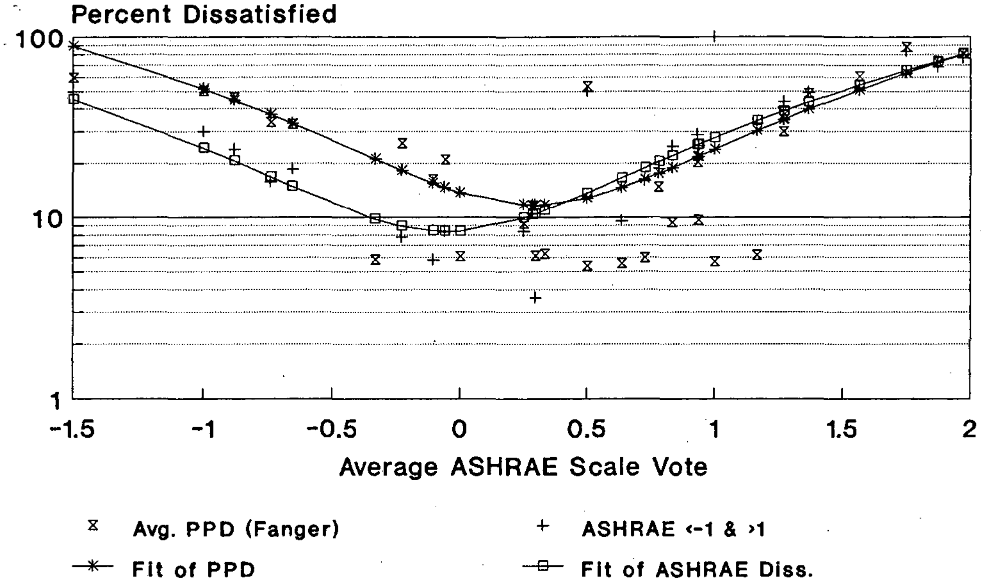


Figure 2O.
Percent Dissatisfied vs. ASHRAE Vote



CHAPTER 3

Energy and Economic Analysis of Conservation in Thai Commercial Buildings

INTRODUCTION

The last few years have seen a boom in both general economic growth and in commercial building construction in Thailand. Accompanying these two phenomena has been a commensurate growth in the demand for electricity. Most of these new buildings are designed for a high level of amenity, including air-conditioning (AC), and thus, are contributing significantly to the 15% annual peak demand growth for the country. Designing and retrofitting buildings to use less energy is a way to avoid both high energy bills for building owners, and strains of rapid growth on the nation's electricity infrastructure. While some energy conservation measures are well understood by Thai designers and engineers, the extent of the potential savings, particularly in the Thai climate, are not always known. Other techniques applied elsewhere, but not so well known locally, may hold conservation promise in Thailand as well. In this paper, we evaluate numerous conservation measures and quantify their energy and economic savings potential in Thai commercial buildings. We focus primarily on commercial buildings that utilize some form of centralized air-conditioning system because of the trends in construction of buildings of this type. However, some of the issues raised are also relevant to older and naturally-ventilated buildings.

METHODOLOGY

Our general approach was to develop typical building prototypes drawn from actual data and field experience, and to simulate the energy impact of modifications to the base buildings using actual weather data and a computer simulation program. The simulation approach was chosen over an approach using statistical analysis of measured data, for instance, because a simulation program facilitates the exploration of many conservation measures, individually or in combination, particularly ones that have not been tried before in Thailand. Below we describe the details of the building prototypes, weather data, and simulation model. Following that, we describe several indices used in evaluating the economic performance of conservation measures.

Building Prototypes

We chose to model offices, hotels, and retail buildings on the basis of a survey of installed air-conditioning over 100 tons[1] because these data include virtually all buildings with central air-conditioning systems with which this paper is solely concerned [Kijwatanachai 1989]. Table 3A shows the breakdown of AC type and chiller cooling capacity (expressed in tons of cooling) by commercial building type in Bangkok and the whole kingdom as of 1986. Water-cooled water chillers (WCWC) make up 87% of all central AC capacity, followed by direct-expansion (DX) units with 10%, and air-cooled water chillers (ACWC) with 3%. In the country as a whole, 32% of the AC tonnage is found in offices, 28% in hotels, and 21% in shopping centers,

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[1] Except for movie theaters outside of Bangkok where buildings with 50 tons and above were included.

department stores, and other retail outlets (from here on referred to simply as retail buildings). Movie theaters, hospitals, and academic buildings represent 10%, 5%, and 3% of national central AC tonnage, respectively. The total share of AC tonnage in offices, hotels, and retail buildings for the whole country is 82% with 70% found in Bangkok. Thus, understanding how Thai offices, hotels, and retail buildings operate, and which conservation measures are effective in each of them, will give a good indication of the conservation potential available in the Thai commercial sector as a whole.

The following building prototypes are all based on models of actual buildings, first benchmarked to within 10% of actual utility bills, and then modified to reflect typical current construction practice. This point is important. Starting with real buildings has advantages and disadvantages. The advantage is that the model description contains rich detail about a building's construction, geometry, configuration, and use. The disadvantage is that every building is anomalous in some respect, and in the absence of a detailed database on typical buildings characteristics, these anomalies can be unrecognized. Nonetheless, even with these caveats, the use of real building prototypes is frequently used, most notably by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) in developing their recommended building standards.

Detailed information was obtained about the prototype precursors from numerous site visits, construction blueprints, and interviews with designers, building engineers, and other building staff. Energy costs were estimated using the current tariff structure in the Large Business category of 1.23 Baht/kWh (U.S.$ .05/kWh) for energy and 229 Baht/kW (U.S.$ 9.16/kW) for monthly peak demand.

Office. A large bank in Bangkok served as the model building upon which the prototypical office was designed. Schedules, intensity of use, and air-conditioning system configuration were retained from the bank building, while size and shape and facade were adjusted to reflect the normal practice. Table 3B lists a summary of the key characteristics of the prototypical office.

Data were compiled from numerous sources of existing commercial building characteristics and energy use in Thailand. Figure 3A shows the distribution of annual electricity consumption normalized by conditioned floor area for six offices in the database, with the office prototype fitted into the distribution. The first bar on Figure 3B shows the end-use energy breakdown for the office prototype. Cooling and HVAC (fans and pumps) use 40%, lights 30%, office equipment 20% and elevators 10% of the total energy.

Hotel. Key characteristics of the Thai hotel prototype are listed in Table 3C. A modern hotel in Bangkok, built originally by a major international chain, was the actual building upon which the prototype was based. Guestroom configurations and use, construction, and air-conditioning system, were retained from actual building. The shape of the plan and facade of the prototype were simplified, while the composition of the public spaces (e.g., lobby, restaurants, meeting rooms, offices, and shops) and the patterns and intensity of use were based on detailed audits of similar hotels in Manila, The Philippines. The hotel prototype is shown in Figure 3C in a distribution of 14 actual Thai hotels for electricity intensity. The breakdown of energy end-uses for the hotel prototype are shown in the middle bar of Figure 3B. Cooling and HVAC consume 60% of the electricity, lights 25%, elevators 10%, and miscellaneous equipment 5%.

Retail. The Thai retail prototype building, whose characteristics are reproduced in Table 3D, is based on a multi-tenant shopping center in Bangkok. Few of the characteristics were altered from the original building. The actual annual energy consumption for three buildings, along with that simulated for the retail building prototype are shown in Figure 3D. The energy end-use breakdown for the retail prototype building, shown in the last bar of Figure 3B, reveals lighting as the major category at roughly 55% of the total electricity bill, followed by cooling and HVAC at 40%, and the remaining 5% shared between escalators and miscellaneous uses.

Weather Data

Hourly weather data from Bangkok for 1985 were used in the analysis. The weather data include temperature, humidity, wind speed, and solar data. Figure 3E shows average monthly solar and temperature data. All weather data except the solar data were gathered by the Meteorlogical Department of the Thai government within Bangkok proper. Hourly total and diffuse horizontal solar radiation data were collected on location by the Department of Energy and Materials of King Mongkut's Institute of Technology in Thonburi (within metropolitan Bangkok). Compared to 30-year normals [Meteorlogical Dept. 1987] the mean monthly, and mean daily maximum and minimum dry-bulb temperatures in 1985 are all within .5 °C of long-term data. Mean monthly relative humidities (RH) for 1985 are within 5 RH percent of the 30-year normals, but are generally lower. There were no long-term solar data available for comparison with 1985.

Temperatures vary within a limited range throughout the year, with the average dry-bulb temperature ranging from 25.5 °C in December to 29.7 °C in April. Similarly, the average total horizontal solar radiation intensity varies only from 324 W/m^2 in October to 406 W/m^2 in March. The direct horizontal component of solar radiation, on the other hand, varys over a relatively wide range, being three times lower in June during the monsoon season than during the dry season in December. Overall, the direct *horizontal* solar radiation is 56% of total horizontal, while direct *normal* is 80% of total horizontal.

Simulation Model

We used the DOE-2.1D building energy program to simulate the response of the building prototypes to the Thai weather and to changes in the buildings' configuration and operation. The DOE-2.1D program is widely recognized as state-of-the-art for this purpose. The program solves, on an hour-by-hour basis, the mathematical relations governing the thermodynamic behavior of a building. It does this in sequential steps through four modules: LOADS, SYSTEMS, PLANT, and ECONOMICS. In the LOADS module, based on user input describing the building surfaces, enclosed spaces, internal usage, and schedules, the instantaneous heating and cooling loads are calculated and then modified to incorporate dynamic effects of thermal mass through the use of weighting factors. The SYSTEMS module calculates the heat extraction/addition of the coils from a large menu of system types and operation parameters. Fuel requirements to operate the primary heating and cooling equipment and pumps are determined in PLANT. The ECONOMICS module calculates the energy costs of operating the building, with the capability of handling complex tariff structures. A good description of the program can be found in BESG [1985]; for more detailed information on using the program and descriptions of the algorithms, refer to the full set of manuals [BESG, 1981-1989].

Economic Indices

Building operators are often more concerned about saving money than saving energy per se. Energy cost savings need to be compared to the extra costs incurred to achieve the savings. In the analysis that follows, we employ several indices of economic performance. Simple payback time is the most universal cost-effectiveness indicator. It is calculated as the ratio of the incremental cost of the conservation and the annual energy cost savings.

$$\text{Simple Payback Time} = \frac{\text{Incremental Cost}}{\text{Annual Cost Savings}} \tag{3A}$$

We also utilize the cost of conserved energy (CCE), an indicator whose chief virtue is that it can be directly compared to the energy prices one expects to face.

$$\text{Cost of Conserved Energy} = \frac{\text{Incremental Cost x Capital Recovery Factor}}{\text{Annual Energy Savings}} \tag{3B}$$

The capital recovery factor in Equation 3B converts the initial investment in energy saving features into an annual payment using a discount rate (d) and conservation feature lifetime (n).

$$\text{Capital Recovery Factor} = \frac{d}{1-(1+d)^{-n}} \tag{3C}$$

A related indicator is the Cost of Avoided Peak Power. This is the quotient of first investment cost and the annual peak demand savings of the building, regardless of when the peak occurs.

$$\text{Cost of Avoided Peak Power} = \frac{\text{Incremental Cost}}{\text{Peak Savings}} \tag{3D}$$

Because conservation investments are often evaluated in the context of other investment opportunities, it can be helpful to calculate the internal rate of return (IRR). This is the discount rate that results in the conservation investment reaping a net present value of zero.

$$\text{Incremental Cost} = \sum_{i=1}^{i=n} \frac{\text{Annual Cost Savings}}{(1+d)^{i}} \tag{3E}$$

Solving Equation 3E for the internal rate of return requires iterating over different discount rates.

RESULTS AND DISCUSSION

In this Chapter we employ the parametric technique of building energy analysis. By varying each parameter one at a time, we can observe its contribution in the overall energy performance of the building. The disadvantage of this approach is that we are unable to account for interactions between parameters that either dampen or accentuate the effect of varying each independently. Therefore, we developed a few cases which combine conservation measures together to illustrate the tradeoffs in an interactive context. The primary basis of comparison used in this study is the percentage annual electricity savings over each prototype's base case. The reader can assume that the peak power and operating cost savings are comparable (in percentage terms) to the energy savings unless otherwise noted. In selected cases, we analyze the cost-effectiveness of conservation measures. The remainder of this section is subdivided into five: architectural, system control, and system equipment energy conservation measures, followed by two illustrative conservation cases (high-efficiency and building energy standard).

Architectural Measures

Architectural measures are those that relate to the building as a whole, to the envelope, or to its interior design and use. Measures relating to systems that maintain control over the indoor thermal environment will be dealt with in later sections.

Orientation. Building orientation has an effect on energy use mainly through the magnitude and timing of solar radiation gains. If the building is square or highly shaded, then orientation is irrelevant. However, if the building has an aspect ratio of greater than 1:1 and is not shaded from direct beam solar radiation when the sun is low in the sky in early morning and late afternoon, then an effect can be seen. With the retail and hotel building prototypes, both of which have aspect ratios greater than 1:1, the energy savings from orienting the long axis of the buildings east-west instead of north-south are .7 and 1.1%, respectively. For these buildings, the peak power savings exceed the energy savings, up to 1.4% and 1.7%, respectively. While the office building is square, one of the perimeter zones is unconditioned (as is often found in Thai offices), so we looked at the impact of orientation of the unconditioned zone. In the base case, this zone faces south. Figure 3F shows the effect of rotating the building around to face the unconditioned zone in different compass directions. It is most advantageous to face the unconditioned zone west, whereas north is the least advantageous. The effect on total energy consumption is small in both cases, on the order of 1% of total energy. However, because of the role afternoon solar gains play in building peak power loads, orienting the unconditioned zone towards the west saves over 2% of peak power.

Infiltration. The quality of building construction can effect the amount of unintended outside air that enters the building. Infiltration occurs in commercial buildings principally when the building is not pressurized by the fans. All of the building prototypes assumed one air-change per hour (ach) infiltration rate. Figure 3G shows the impact of varying the infiltration from .2 to 3 ach. Hotel and retail buildings show positive energy savings from reducing infiltration while the office does not. This is because infiltration occurs during the daytime in unoccupied hotel guest rooms and prior to shops opening in mid-morning, whereas daytime infiltration in the office occurs only on weekends. The benefit of reducing the infiltration below one ach is minimal, but the penalty for allowing it to rise substantially above that is high: energy use increases of 5% to 7% occur and are accompanied by equally high penalties in peak demand and equipment sizing. It is also possible that these estimates of the implications from increased infiltration are understated: this is because DOE-2 does not model moisture absorbing into and later evaporating from, building materials and furnishings; given the high humidity conditions that exist in Bangkok, in an actual situation higher energy expenditures could result from these higher latent cooling loads.

Opaque Walls and Roofs. The effects of thermal mass in offices and retail buildings are shown in Figure 3H. This plot differs from the others in this Chapter in that the savings relate to the parametric run with the lowest mass rather than to the base case. Office walls exhibit the largest effect from increasing the thermal mass, with savings of 2.5% of total energy over the wall mass range of 100 to 500 kg/m^2. Hotel walls show only a 1% effect and the office roof effect is negligible, primarily because it is such a small percentage of the overall envelope area in a 12 storey building.

Insulating the walls to lower the thermal conductivity saves 3.5% of total energy in hotels, but shows a marginal impact with offices (see Figure 3I). This is probably due to the 24-hour operation of the hotel and the systems that regulate the heat gains whereas in the office building, some of the heat gains are delayed by the thermal mass and dissipate overnight. Roof thermal conductivity has little impact on energy use for these same reasons. It can, however, have an impact on local comfort if not properly accounted for in the air-conditioning system design.

Light-colored walls absorb less solar radiation than dark-colored walls, resulting in lower surface temperatures and hence lower conduction heat gains. Figure 3J plots the percent of total energy savings over the solar absorptance range of .1 to .9. Even though the office has the smaller proportion of opaque wall to gross wall area, it has a greater response to changing solar absorptance. Again, the hours of building operation are the likely explanation.

Windows. High solar intensity in Thailand results in the potential for high radiation heat gains through building window apertures. Conduction heat gains also occur through the typically single-pane window construction. Therefore, any effective energy conservation design strategy includes provisions for handling heat gains through windows. A primary issue is the amount of glazed area in a building. Figure 3K compares the energy savings vs. window-to-wall ratio (WWR) for the three building prototypes. Note that the shading coefficient (SC) of the glass influences the amount of solar energy penetration, which in turn differs in each case. The shading coefficient is defined as the ratio of solar heat gain through a window to the solar gain through a reference glass. The office, which has the lowest shading coefficient (SC=.34) nonetheless, displays the greatest impact of varying WWR, ranging ± 6% energy savings over .1 to .9 WWR. This is significant because of the current popularity of glass curtain-wall construction for offices in Bangkok. The office is more susceptible than the hotel or retail buildings to SC as well, as shown in Figure 3L. This latter plot shows that, even with a modest WWR of .5, choosing a glazing with a high SC for an office building will be costly in operating expenses. Hotels and retail buildings by virtue of typically lower WWR and different operating schedules are not impacted as much either in relative or absolute energy savings terms.

Shading. Besides attenuating solar gains by selecting glass with a higher SC, shading devices can be attached to window systems. These shading devices may be either external or internal. External shading devices are in fact part of the vernacular design, and often are a major aesthetic expression of a building, taking on complex shapes, geometries, or colors. But typically, external shades take the form of horizontal overhangs and/or vertical fins. In the prototypical office building, already "shaded" with .34 SC glass, large fins and overhangs can provide up to an additional 5% energy savings as shown in Figure 3M. In this plot, the shade dimension is given in percent of the window height for overhangs and in percent of window width for fins. The plot also shows that little energy savings benefit is derived from sizing fins larger than 10% of the window width, and averages about 1% overall. Specific orientations could potentially benefit more from larger fin depths but this effect is not explored here. Overhangs or fins were simulated on the hotel and retail buildings. At a depth of 100% of the window height, overhangs show roughly 2% energy savings for both building types as shown in Figure 3N. Fins show about .5% savings over the range of fin depths.

Internal shading devices were also simulated. The three building prototypes all assumed venetian blinds were present and that occupants closed them down when incident solar radiation exceeded a threshold intensity (126 W/m^2), and that when the shades were closed, solar gains were reduced by 25%. The results show that less than 1% savings accrue when shades are triggered by half the solar intensity of the base case, and conversely, little is lost by not using them at all. Occupants may want to pull the blinds for other reasons, such as to reduce glare or enhance privacy.

Lighting and Internal Process Loads. Lighting is a significant end-use in commercial buildings for two reasons: 1) it uses energy directly to provide light, and 2) it generates waste heat that must be removed by the air-conditioning system. Internal process loads are those from any device that uses energy and generates heat, including appliances such as refrigerators in guest rooms or photo-copying machines, computers, and electric typewriters in offices. Particularly as offices environments become more automated, internal process loads will rise, creating the impacts shown in Figure 3O. Different schedules of usage explain the different energy savings seen between lighting and equipment in offices. Cutting the lighting power density by half yields a total energy savings of roughly 18%. Many options exist for installing lighting systems that use less than 10 W/m^2, while still maintaining adequate luminance levels [Usibelli 1985; Piette 1989]. Although, there is currently no apparent market for energy-efficient models of office equipment, it is included in our analysis simply to illustrate the magnitude of the impact of automating offices. Figure 3P depicts how much total energy is saved by implementing lighting power density reductions in hotel and retail buildings. The diversity of lighting in each of these buildings dictates lighting power reductions through any means be considered in terms of a floor-weighted average. The savings for the retail building are nothing short of dramatic; total energy savings equal three-quarters of the percentage reduction in lighting. For instance, a 20% reduction in lighting results in a total 15% energy savings. Hotel savings from lighting efficiency improvements are comparable to those for offices.

Daylighting. The use of natural light to augment or replace artificial light in offices has the potential to realize some the savings discussed above. In fact most buildings admit natural light already. Daylighting technology consists of controls for the artificial lighting to reduce their energy consumption when natural lighting is sufficient. To fully realize the benefits of daylighting, however, the building ideally is designed to exploit the natural light resource through proper fenestration design, interior design and layout of spaces, and through advantageous placement and wiring of overhead artificial lighting. It is beyond the scope of this study to discuss techniques for designing a daylit building. We will instead concern ourselves with how high the potential savings might be in Thai offices.

There are two basic types of daylight control systems: stepped and continuous control. Both are actuated by a luminance sensor that is calibrated to maintain the light levels at desk height (75 cm), 3 meters back from the window, at 500 lumens. Only perimeter zones (with a depth of 6 meters) are equipped with daylighting controls; the core zone retains the base lighting configuration. The energy savings from stepped controls as a function of the number of steps is shown in Figure 3Q. Simple on/off controls (i.e., one step) achieve only 3% energy savings in the office prototype. In addition to showing only modest savings, on/off controls can be distracting or even irritating to building occupants when they switch between being on and off. Three steps or greater yield much higher savings up to 9%. Continuous dimming controls are a more refined version of the stepped controls, providing more visual comfort to building occupants through smooth transitions between all artificial light and all natural light regimes. The energy savings from daylight utilization with continuous dimming devices is depicted in Figure 3R. Depending on the manufacture, these devices can consume different amounts of power even when the lights are fully dimmed: the plotted curve shows the total energy savings from continuous dimming devices that consume from 0 to 50% of full lighting power.

The optical and thermal properties of window glass are also important for daylighting. The ideal glazing material is one that selectively repels all but the visible portion of the solar radiation spectrum. No such product yet exists, but there are commercially available glasses with low-emittance coatings that do admit proportionally more visible than thermal gains. To explicitly account for the tradeoff between heat and light gains through glass with different properties, we plot the savings potential vs. the ratio of the shading coefficient and the visible transmittance (called K_e) in Figures 3S and 3T. Figure 3S shows results using a shading coefficient of .34 (base case) whereas Figure 3T uses a SC of .70. The family of curves in each figure correspond to different overhang depths. Note that these data reflect the use of continuous dimming controls with 30% minimum power draw. Energy savings are twice as high with a K_e of 1.3 as with a K_e of .3. Overhangs increase the savings a few percent with SC=.34 glass. However, as can be seen in Figure 3T with less tinted glass (e.g., SC=.70), overhangs make a significant difference in the energy savings from daylighting. Maximum savings range from less than 6% to almost 12% depending on the depth of the overhang. It is clear that, even with a high ratio of visible light to heat gain (e.g., 1.3), the heat gains associated with unshaded relatively high SC glass (e.g., .70) erode the daylighting savings significantly. Good daylighting design in Thailand must include provisions for reducing the solar heat gains through the windows.

Summary. Figures 3U through 3W summarize the savings potential for individual architectural conservation measures applied over each measure's parameter range expressed in earlier figures for offices, hotels, and retail buildings, respectively. From these Figures, it is immediately apparent which architectural measures have the greatest influence over energy use in the building prototypes. The reader should refer to earlier discussion and related Figures for information on the parameter end points and a more complete depiction of the relationship between the measures and energy savings.

Air-Conditioning System Control Measures

Zone Air Temperature. Few measures affect energy use in a commercial building as much as the setpoint temperature of the conditioned space. Figure 3X illustrates this point over the range of 20 °C to 30 °C for the three building prototypes. This temperature range was chosen to reflect observed values at the low end [Busch 1988] and a thermally acceptable temperature level as determined through a field survey of thermal comfort in Thai offices [Busch 1990] at the high end. The hotel is most sensitive to changes in the thermostat setting, ranging from more than -40% to 20% total energy savings. This is almost certainly due to the constant (as opposed to intermittent) operation, and also because guestrooms, unoccupied and uncooled during parts of the day, require larger systems to cool down the accumulated heat gains when guests return and turn on the fan coil units in their rooms. The resulting equipment oversizing means that it operates at most other times in a less efficient manner. Offices are nearly as sensitive as hotels, going from -20% to 15% savings. It is interesting to note that while the peak demand savings lag behind energy savings for the hotels and retail buildings, in offices it is the opposite -- peak demand is conserved up to 1% more than energy is conserved at a zone air temperature setting of 30 °C.

Certainly a factor in explaining the large negative savings shown at the low end of the temperature scale is that fan sizes are hugely increased to meet the peak cooling loads (by a factor of 5 in the office; by a factor of 10 in the hotel). Given that the air-system operates at constant volume, the fans continuously push that much more air at all times. A more conservative scenario would have the supply-air temperature reduced along with the setpoint temperatures, to take advantage of the better chiller part-load performance characteristics. We take a closer look at supply-air temperature next.

Supply-Air Temperature. The supply-air temperature is an interesting parameter because it embodies important trade-offs. First of all, fans are generally sized to meet peak cooling loads based on a particular supply-air temperature. Lower supply-air temperatures require less air-flow (and therefore lower fan capacity) to meet cooling loads, but demand more capacity (and energy) from the chillers. Logically, the converse is true of higher supply-air temperatures. Thus, supply-air temperature affects whether more AC energy is expended by fans or chillers, and what the optimal supply-air temperature is depends on the relative efficiencies between them [Usibelli 1985)] The supply-air temperature also affects the amount of latent cooling that occurs; in Thailand, with its high humidity levels, that is an important consideration for human comfort and health, and the preservation of documents and fabrics.

Figure 3Y shows the energy savings as a function of supply-air temperature. Each of the buildings with their respective systems behave differently. The office building achieves energy savings up to 2% at low supply air temperatures, whereas at the same 8 °C, the hotel consumes 6% more energy than the base case. This contrast can be explained as follows: the office air-distribution system, with low static pressure but also low-efficiency fans, is apparently less efficient to operate than the chiller, hence the energy savings. The hotel, on the other hand, has most of its fan capacity in fan coil units, which also are inefficient, but which operate at such low static pressure, that little offsetting savings occur through reduced operation as compared to the increased chiller usage. The result is that only negative savings are achieved for the hotel. The retail building yields different results altogether, where the system configuration seems to dominate the result. There, the central water chiller system provides only 20% of the cooling while individual split-system units cool the bulk of the building. Overall, roughly comparable efficiencies appear to exist between the cooling and air-distribution sides, as seen in Figure 3Y, where savings are essentially zero over the supply-air temperature range, and the tradeoffs cancel each other out. The lesson here is that careful examination of relative equipment efficiencies and system-type is needed to ascertain optimal supply-air temperature and also that simulation is probably the best way to do this because of part-load operation considerations.

Supply-air temperature can be controlled in different ways. It can be fixed to a constant level (as assumed for the three Thai building prototypes), or it can respond to the cooling needs of the warmest zone, or it can be set by a pre-determined schedule according to outside temperature. Under the conditions treated with these buildings, however, the control type had little or no effect on energy consumption.

Fan control. All of the base case systems are constant volume systems. We did explore the use of variable air volume (VAV) systems in place of these. VAV systems differ from one another mainly in how the fan speed is modulated. There are three main technologies for doing this: discharge dampers, inlet vanes, and variable speed drives. Figure 3Z shows the energy savings over the respective constant-volume base cases when the three Thai building prototypes employ these fan control techniques. Discharge dampers are the least desirable; savings are in fact negative when the retail building uses them. The offices and hotels save 4% and 2%, respectively. Inlet vanes are the intermediate fan control technique in terms of energy savings, with offices and hotels saving nearly 8%. Variable speed drives save the most; offices conserve 9% and hotels 10%. Because of the system configuration in the retail building, it does not seem to exploit the advantages of a VAV system.

Outside Air. Human health requires that some fresh air be brought into the building and mixed with recirculated air. This is done for dissipating odors and diluting air-borne contaminants from furnishings, smoking, cooking, etc. Because outdoor air is generally hot and humid in Thailand, there are energy implications in choosing the quantity of outdoor air to be brought in. Figure 3AA plots the energy savings for different amounts of outdoor air in terms of cubic feet per minute (cfm) per person. The hotel shows the most substantial savings, reaching 15% if outdoor air is reduced to 5 cfm/person. The office and retail building respond similarly, saving up to 5% at the 5 cfm/person level. For the office, a 5 cfm/person ventilation level extends to a 7.5% peak power savings, and for the retail building, to a 6% savings in peak power.

In some climates it can be advantageous to increase the amount of outdoor air beyond the minimum level at certain times when temperatures and humidities are below those of the return air. This is the so-called economizer cycle. The base case design in each of the building prototypes assumed a fixed outdoor air damper (i.e., no economizer capability). Simulations were performed with an economizer cycle activated when 1) the outdoor temperature was below the return air and, 2) when the outdoor air enthalpy was below return air enthalpy. Neither case generated any savings of any sort with any of the building prototypes, and in fact led to negative savings in the office when activated by temperature.

Pre-Cooling. Studies have shown that pre-cooling the building prior to occupancy can reduce peak loads and the needed air-conditioning system capacity at the expense of increases in energy use [Eto 1985; Busch 1988]. In that sense, it is not an energy conservation technique per se, but rather a load management strategy. We ran the Thai office prototype AC system for one, two, and three hours prior to office hours to assess the relative energy losses and peak savings. These results are shown in Figure 3AB. We looked at pre-cooling before every working day (all days except Sundays), and at pre-cooling on Monday mornings only, on the theory that peak days tend to occur on Mondays after a weekend of heat gains have gathered within the building thermal mass. The plot shows that energy penalties run about 2.5% per extra hour of pre-cooling, whereas the peak savings approach only 1% after 3 hours of pre-cooling and are less for shorter pre-cooling durations. Interestingly, though, there is no difference in the peak savings between pre-cooling all days and pre-cooling on Mondays only. This confirms the hypothesis that building electricity demand peaks tend to occur on Mondays in hot climates.

So, it obviously it is not efficient to pre-cool the building on all days, and though the savings are very modest, peak demand can be trimmed slightly by pre-cooling on Mondays or on the day after a holiday. However, under the current utility rate structure for large businesses, this strategy does not result in operating cost savings.

Night Fans. Night ventilation of the building under certain circumstances can help to reduce daytime cooling loads, and thereby reduce AC system design capacity and peak demand. The building fans are turned on to circulate outside air through the interior spaces under different control strategies. This technique is not applicable to hotels which require 24-hour conditioning (except when running the economizer cycle which, as mentioned above, is unattractive). We chose to look at the use of fans at night in the office prototype. We looked at control logic that turned on the fans when both the outdoor temperature was below a threshold value (29 through 31 °C) and the indoor-outdoor temperature difference was greater than some given values (1 through 4 °C). We also examined simple pre-scheduled fan usage. None of the simulations revealed any savings potential using this measure. In fact, in most cases the peak demand savings were actually negative and 2 to 3 times higher on a percentage basis than the expected negative energy savings. There is no apparent justification for running fans at night in daytime-occupied Thai commercial buildings.

Air-Conditioning System Equipment Measures

Chillers. Within the cooling end-use which, as we have seen, comprises from 40 to 60% of the total energy budget, chillers are the major piece of energy-consuming equipment. Scale economies exist with chillers. The larger units tend to use the more efficient technology, (i.e., centrifugal chillers coupled with a cooling tower for lowering condenser temperatures). In the smaller sizes (for commercial applications), one typically sees air-cooled reciprocating chillers with lower efficiencies. Coefficient of performance (COP) is the usual figure of merit in comparing chiller efficiencies and is calculated as the ratio of cooling output to electrical input. Energy savings by COP are shown in Figure 3AC. At a COP of 3.5, we modeled reciprocating chillers, but at higher COPs we used water-cooled centrifugal chillers. The hotel shows the most promise in the application of an efficient chiller, saving 10% with a 5.5 COP unit. The office follows with a savings of 7% while the retail building shows a 5% savings. Likewise, a large energy cost is associated with using an inefficient chiller on the hotel, losing 12% when dropping the COP from 4.0 to 3.5. As we have seen elsewhere, the base case building operation and system configuration have a large effect on the size of total savings. In the case of the hotel, the day-night operation of the system means that efficiency improvements in energy-using equipment translate into large savings. For the retail building, the use of split-system air-conditioning units in the shops limits the benefits from improvements to the central system serving the circulation zones where more efficient options exist.

Fans. Fan equipment is also available in a range of technologies and efficiencies. The types are airfoil and backward inclined at the high end and forward-curved and vaneaxial fans at the low end. Scale economies exist in fan technology as well, with large built-up systems using the more efficient technologies. Larger, more efficient motors are also more prevalent in the large fan sizes. One of the tradeoffs involved in the choice of fan size is that a larger fan usually implies a longer duct run resulting in an increase in the static pressure that, in turn, increases the energy consumption of the fan. We look at both fan efficiency and static pressure for potential energy savings in Figure 3AD and 3AE. Using fans that are 70% efficient (over the base 40%) can save close to 8% in hotels, 6% in offices, and 2% in retail buildings. Conversely, using 30% efficient fans can result in 6%, 5%, and 1% energy consumption increases in the hotel, office, and retail buildings, respectively. In Figure 3AE the relationship between static pressure and energy savings is plotted. Doubling the static pressure from 2 to 4 inches causes negative energy savings of 17% in the hotel, 15% in the office, and 8% in the retail building. The energy penalty for increases in static pressure is high.

Because some engineering designers put in large safety factors when sizing equipment, we looked at how much more energy fans use if they are oversized. This can be especially costly for a constant volume system because there is no mechanism for reducing flow (and hence energy consumption) when zone cooling loads are already met. Figure 3AF displays the fan oversizing penalties. Oversizing of 10% has a 2% total energy increase in the hotel and office, and 1% increase in the retail building; fan oversizing of 50% results in 10% and 4%, respectively. Careful cooling load analysis to avoid the need "to be extra sure" can save energy.

Pumps. Pumps circulate chilled water around the building to provide a cooling effect to the coils in air handling units and then back to the chiller. Generally, these pumps are run at constant speed, but can be outfitted with variable speed drives, thereby saving pumping energy. Although chilled water pumping energy makes up only a small portion of the total energy expenditure in a building (i.e., between .5% and 2.5%), the savings for using variable speed pumps in the hotel were almost 2%, and 1.5% in the office, and less than .5% in the retail building.

Thermal Storage. Electricity load management is an issue for both building owners who are interested in controlling their demand payments, and utility planners who are trying hard to keep up with demand growth and maintain system load factor. The air-conditioning system contributes significantly to the building peak demand and is therefore an attractive target for load shifting to a period when other electricity-using equipment is dormant. Thermal cool storage is one technique for shifting the electrical AC load by storing chilled water, ice, or some other phase-change material, that can be used later used to meet part or all of the cooling load. The economic climate for cool storage in Thailand and the other ASEAN countries was examined in earlier work and found to be attractive [Wyatt 1986]. A general explanation of the technology can be found in Piette [1988] and more detailed design information in EPRI [1985].

We looked at the use of a chilled-water cool storage system in the Thai office prototype under a few different control strategies. The partial storage strategy runs the chiller continuously, to store "coolth" during unoccupied hours, and to augment the cooling output of the storage during occupied periods. Full storage seeks to supply all of the cooling from storage during the building's occupied period, and to run the chiller only during the unoccupied period to recharge storage. The demand-limited strategy is a hybrid of the two: the chiller runs to either recharge storage or meet cooling load directly until some pre-determined, threshold building electrical load is reached whereupon the chiller switches off and cooling is provided solely by storage. Table 3E shows the results of thermal storage by strategy.

One can see the implications of operating strategy in storage and chiller sizing. Partial storage requires the smallest capacity of each because neither is used to meet the whole load. Full storage, on the other hand, needs a large storage tank in order to satisfy the entire cooling load during the peak cooling day, and also needs a large chiller to be able to charge the storage in the remaining off-hours. The table shows the resultant electricity purchases and savings in terms of energy, demand, and cost, assuming chiller cost at U.S.$ 400/ton and storage cost at U.S.$ 75/ton-hr.

Demand-limited storage saves the most peak power, saving 37%, while full storage is next, saving 32%, and partial storage saves 18%. Cooling energy purchases are the same for all three. The investment cost for the storage tank and peripherals are traded off against chiller capacity and operating cost savings, expressed as a simple payback period. Partial storage has the shortest payback at 4.3 years, followed by the demand-limited strategy at 6.3 years, and full storage at 9.5 years.

Cool storage could be used in lieu of new power plant capacity. Some electric utilities in the U.S. have offered incentives to commercial customers to invest in cool storage. From the point of view of the electric utility, it is important to know the equivalent capacity cost of thermal cool storage in order to be able to compare it with supply alternatives. Cost of avoided peak electricity is shown for the three cool storage strategies in Table 3E. In order of increasing U.S.$/kW they were 302, 580, and 877, for the partial, demand-limited, and full storage strategies, respectively. Note that these figures indicate nothing about the operating energy or cost savings, only investment. They also take no account of the timing of the building peak load and how much it coincides with that of the utility. In that sense, these figures are prepared from the perspective of the building owner who is not concerned with when the demand occurs, but only with how large it is because no time-of-use tariff is in use for Thai businesses. For the same reason, the full storage strategy looks unattractive in comparison to the others; should a time-of-use demand tariff go into effect and should there be a large differential between the on-peak and off-peak rates, then full storage could very well be more economic than the others. Currently, however, partial storage is the most suitable cool storage strategy to pursue in offices in Thailand.

Analysis of thermal storage using the partial storage strategy in hotel and retail building prototypes was similarly performed. Table 3F shows the results. The continuous operation and pattern of loads of the hotel dictate that the storage be sized modestly because of limited daily opportunities for recharging. Peak demand reduction is accordingly modest, saving 12% of the base peak load. Nonetheless, cool storage is so cost-effective in hotels that it has a zero payback time and *negative* cost of avoided peak power. That is, the incremental cost of the storage system is more than offset by savings in installed chiller capacity.

Thermal storage sizing (relative to the cooling load) and cost-effectiveness in the retail building prototype are more similar to the office case. Simple payback time is a shorter 3.1 years, while the cost of avoided peak power is slightly higher at 367 U.S.$/kW.

Cogeneration. When electricity is generated in a typical thermal power plant, there is a large amount of heat that is rejected unused into the atmosphere. Advocates of increasing the efficiency of society's use of energy have pointed towards coupling the generation of electricity with some productive process requiring heat, thereby squeezing more utility out of the overall energy conversion process. This coupling, known as cogeneration, has been applied primarily in industrial sectors where large process heat requirements exist. Commercial buildings have interesting potential for cogeneration applications because they always have on-site electricity needs, and often have a process heat load for domestic hot water (especially in hotels) and/or for thermal cooling equipment.

The Thai office prototype building was simulated using gas-turbine generators coupled with exhaust heat recovery to a two-stage absorption chiller. The gas turbine was assumed 24% efficient in electricity conversion at maximum output, and the exhaust heat recovery maximum was 55%. The absorption chiller had a COP of .8. Since natural gas is not currently sold to commercial customers in Thailand, economic calculations used the price paid by the electric utility, or U.S.$ 2.4/kJ. Without the electrical chiller, the building electricity demand from all the other end-uses was about 500 kW, so we looked at generator sizes less than and in excess of the building's electrical demand. The cogeneration plant was tested in several operating modes: tracking the thermal load, tracking the electrical load, and running at maximum output throughout. Any electricity generated in excess of the building's need was assumed to be sold back to the electric utility at the same effective electricity purchase price of the utility in the base case (i.e., U.S.$ .087/kWh). This price was chosen for illustrative purposes only since no such buyback provision yet exists in Thailand, but it is part of the country's latest five-year economic plan [NESDB 1985] to develop such an arrangement to encourage private power production in the way it has been in the U.S. under the Public Utilities Regulatory Policy Act (PURPA) legislation.

Table 3G shows the cogeneration results. The capacity factor relates the actual electricity production to that which the generator could theoretically produce over the same period. As one moves into the larger capacity units, the capacity factors fall under the thermal and electrical tracking modes. The payback time, calculated by dividing the net operating savings into the investment cost of U.S.$ 1000/kW, generally follows an inverse relationship to the the capacity factors. Thermal tracking is the least attractive operating mode because of the low price of natural gas in relation to electricity, and because of under-utilization of the cogeneration system. This is dictated by the structure of thermal and electrical loads in the office building; in a building with a better match of thermal and process heat demands (like a hotel with guest and laundry demand for hot water, for instance) the thermal tracking strategy would be more attractive. In terms of thermodynamic efficiency, however, the thermal tracking is the best because it assures that none of the heat is wasted. Running the cogenerator at full output has the shortest payback time (2 years at every capacity simulated) because of the healthy revenues collected on electricity sales to the utility. Although the utility does not now purchase power from private power producers, this particular scenario of cogeneration in an office building should be of particular interest in Thailand since the evening period when the Thai power system generally experiences its greatest demand is also when all of the cogenerator's output is going back to the utility. When tracking the building's electrical load, the 300 kW cogeneration system has a payback of 3.5 years, increasing to 6.8 years with the 700 kW system. In the absence of a buy-back contract with the utility, this is the best operating mode to use.

Cogeneration and Thermal Storage Combined. One further configuration using a hybrid of cogeneration and thermal cool storage was simulated. This is interesting because cool storage can help provide a steady process heat load during the storage recharging period. We looked at the same 300 kW cogeneration plant as above with the cool storage sized and operated in the partial storage mode. Table 3H shows the results for this system under the three cogeneration operating modes. Payback times are essentially the same as the cogeneration only scenario for both electricity tracking and maximum output modes. The payback for the thermal tracking mode increases to 8.1 years, despite the steadier heat demand. To use the thermal tracking mode, this building would need to use a smaller generator whose waste heat capability more closely matched the building thermal needs.

Non-Electric Cooling. Another strategy for reducing peak electric demands is to utilize thermal cooling technology that runs on fuels other than electricity, or even waste heat [Ogden 1988; Brodrick 1988]. We examined chillers operating on the absorption cycle and engine driven, vapor compression chillers, both powered by natural gas. Using equipment efficiency assumptions and installed cost data found in Ogden [1988], the above gas cooling systems were simulated in the three building prototypes, and their energy and economic performance assessed. The economic calculations used natural gas prices paid by the electric utility and assumed the incremental costs above those for a conventional chiller only (i.e., for new installations and not for replacement of existing equipment). The results are presented in Table 3I.

Due to higher efficiency, the engine chiller out performed the absorption chiller; yet both had payback times under three years. Non-Electric cooling was most advantageous in retail buildings, then hotels, and finally offices. From an avoided peak power perspective, the engine chiller was slightly superior to the absorption chiller, ranging around U.S.$ 300/kW.

Summary. Figures 3AG through 3AI summarize the savings potential for individual air conditioning control and equipment conservation measures applied over each measure's parameter range expressed in earlier figures for offices, hotels, and retail buildings, respectively. Thermal storage, cogeneration, and thermal cooling technologies are not shown in the figures because the factors that make them cost-effective are not strictly related to energy savings, but more towards electricity/alternate fuel price, and energy/demand charge differentials.

High-Efficiency

To illustrate the potential savings through the use of multiple conservation measures, we have combined the most promising measures (as revealed above) into high-efficiency cases for the office, hotel, and retail building prototypes. Any interactions between measures are embedded in the performance of these cases making them more realistic than simple addition of the savings from individual measures.

We evaluated individual measures for inclusion in the high-efficiency cases, not only for high-efficiency gains, but also for cost-effectiveness. The high-efficiency cases were not strictly optimized for economic performance; instead, measures were chosen for maximum energy performance and screened for cost-effectiveness. In fact, only a few measures were screened out in this way.

Our economic analyses obtained energy, power, and operating cost savings values as compared to the base cases, and on the basis of incremental costs of the conservation measures, calculated several indices of economic performance: cost of conserved energy, simple payback time, and internal rate of return. Costs of conservation measures were obtained from a mix of local sources [Nimboonchai 1988; Kijwatanachai 1989; Chevasutho 1988; and Seehanath 1988], and U.S. sources [Piette 1989]. We assumed a seven percent real discount rate and, for most measures, 20 year lifetimes. Some conservation measures allow HVAC equipment to be downsized, resulting in potential investment cost savings. We also prepared the economic indices using the incremental investment cost net of the HVAC downsizing "credit." The resultant energy and economic performance of the high-efficiency cases is shown in Table 3J.

All of the high-efficiency cases used the same basic AC system configuration: a VAV system with variable speed fan and pump drives, 70% efficient fans, chiller COP of 5.5, a temperature setpoint of 28 °C, and outside air flow of 10 cfm/person. The architectural measures that were employed in the high-efficiency cases varied by building prototype; those we discuss below.

Office. The following changes from the base case form the high-efficiency office: window overhangs with a depth of 10% of window height, window-to-wall ratio of .3, solar absorptance of .2 for the opaque walls, and lighting power density of 10 W/m^2.

The high-efficiency office saves 45% of total electricity over the base case. The CCE is U.S.$ .016/kWh, well below the average electricity rate of U.S.$ .087/kWh (including demand charges). The simple payback time is 2 years, the IRR is 51%, and cost of avoided peak power U.S.$ 508/kW. When credited with HVAC downsizing, the high-efficiency office becomes twice as attractive economically.

Hotel. With the AC system configured as above while retaining the fan coil system in guest rooms, the high-efficiency hotel generates savings by overhangs depth of 40% of window height, glass SC of .3, WWR of .3, wall solar absorptance of .2, U-value of the wall of .2 W/m^2-°C, and lighting power reduction of 40%.

The hotel high-efficiency case saves 51% over the base case. The CCE is U.S.$ .015/kWh, the IRR is 44%, the payback time is 2.3 years, and the cost of avoided peak power is

U.S.$ 849/kW. A roughly 60% improvement in these economic measures results from the HVAC downsizing credit.

Retail. This case used glass with a SC of .3, roof solar absorptance of .2, and lighting power reduction of 40%. Note that the VAV system is used throughout the retail building, i.e., that the split-systems in the shops were replaced.

The retail building high-efficiency case saves 56% of total electricity over the base case. This case is the most cost-effective compared to the office and hotel cases. The CCE is U.S.$ .013/kWh, the simple payback is 1.7 years, the IRR is 60%, and the cost of avoided peak power is U.S.$ 453/kW. On the other hand, the improvement in cost-effectiveness due to HVAC downsizing is much more modest in the retail as compared to the office and hotel buildings because of the sizing penalty involved in going from a distributed to a central system.

Building Energy Standard

An energy standard for new commercial construction has been proposed [NEA 1989]. It is currently under consideration for voluntary compliance only. The Thai standard draws on earlier work in neighboring countries [DBCD 1979; Busch 1987; Deringer 1987]. The standard aims to reduce energy use through provisions for the building envelope, lighting, and space-conditioning systems. Table 3K compares some of the key criteria of the standard with those of the base cases of the three prototype buildings (shown in parentheses). The lower half of Table 3K shows the results of, and inputs to, the Overall Thermal Transfer Value (OTTV). The OTTV approach attempts to capture the key parameters of the building envelope causing cooling demand on the chiller. The OTTV equation for walls, as formulated in Thailand, follows the approach found in DBCD [1979] modified for local solar radiation conditions. The equation has three terms each for different heat transfer pathways: conduction through the opaque wall, conduction through the fenestration, and radiation gain through the fenestration.

$$\mathrm{OTTV} = U_w\,(1-\mathrm{WWR})\,TD_{eq} + U_f\,(\mathrm{WWR})\,\Delta T + \mathrm{SC}\,(\mathrm{WWR})\,\mathrm{SF} \qquad (3F)$$

where,

U_w = U-value of the opaque wall (W/m^2–°C);
WWR = Window to wall ratio (dimensionless);
TD_{eq} = equivalent indoor-outdoor temperature difference for the opaque wall (°C);
U_f = U-value of the fenestration (W/m^2–°C);
ΔT = indoor-outdoor temperature difference for the fenestration (°C);
SC = fenestration shading coefficient (dimensionless);
SF = solar factor (W/m^2).

The U_w, WWR, U_f, and SC are all parameters chosen by the building designer. The other terms, TD_{eq}, ΔT, and SF are quantities stipulated by the standard. TD_{eq} varies according to the solar absorptivity of the exterior wall surface, ranging from 14 °C to 18 °C, while ΔT is a fixed 5 °C. SF has been set at 160 W/m^2 but is corrected for orientation and non-vertical slopes. Thailand has set the OTTV compliance level at or below 45 W/m^2.

The prototype buildings were modified to minimally comply with the standard.[2] Note that many combinations of parameters can be used to comply with the OTTV standard, but that we illustrate only one here. The energy savings were 23% in the office, 35% in the hotel, and 42% in the retail building. The major contribution to these savings obtained from the standard comes

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[2] Where a base case parameter was equal to or "better" than the level set by the standard, it was left unchanged.

from the lighting power density provisions, saving both lighting energy directly and cooling energy (and capacity) indirectly. No economic analyses were performed for the standard, but are probably as cost-effective as the high-efficiency cases discussed above.

CONCLUSIONS

Energy conservation measures have been evaluated for commercial buildings in Thailand by means of computer simulation. A prototypical office, hotel, and retail building were developed based on actual Bangkok buildings, and simulated in the Thai environment. The best measures combined into high-efficiency cases for each prototype cut energy and peak power usage, and electricity bills in half as compared to typical design practice. When considering the cost of installing the measures that make up the high-efficiency cases, they remain attractive by being highly cost effective. Compliance with the proposed energy standard for new buildings lowers energy intensity by approximately one third overall, with substantial variation among the building types. Taken individually, the conservation measures demonstrated the following savings.

Architectural Measures

Architectural measures showing the greatest impact on energy use are those relating to fenestration and lighting.

- Window area, glass shading coefficient, and, for offices, the use of external shading devices, are all critical features that can each result in up to a 5% increase or decrease in total energy consumption.
- Energy conservation in lighting saves both directly in lighting energy and indirectly in cooling load reductions; this leads to dramatic savings potential of 20% to 35% for cutting lighting power density in half.
- Daylighting can cut energy use by 6% to 15% depending on the design. Lower savings result when the daylighting design fails to limit solar heat gains through windows.
- Insulating the opaque wall section of hotels saves almost 4%, but in offices and retail buildings the savings are negligible.

Air-Conditioning Measures

- In the use of an air-conditioning system, the single most important parameter is the zone thermostat setpoint. Savings reach above 10% for this measure alone within a temperature range proven acceptable to Thai office workers. This is also a no-investment-cost measure.
- The use of a VAV system with variable speed fan drives in place of constant volume can save between 8% and 10% in offices and hotels.
- Efficient chillers and fans each indicate savings potential in the 5% to 10% range.
- Reducing outside air quantities in hotels to 10 cfm per person saves 10% of total energy; about 4% could be saved in offices and retail buildings ventilated to the same degree.
- Conversely, high static pressures in the fan duct system, or fan oversizing, or inefficient chillers, or excessive quantities of outside air, all carry large energy penalties.
- Thermal storage employing a partial storage strategy can significantly reduce peak demands and associated charges in a cost effective manner, particularly in hotels where the chiller cost savings can be greater than the extra cost of the storage system.
- Should natural gas become available to commercial customers in Thailand, then cogeneration can be economically attractive, particularly when sized to match the thermal load from the absorption chiller, but operated to track the building electrical load. If excess

electricity can be sold back to the utility at a price close to the current retail price of power, then operating the generator at maximum output is the best strategy, almost independent of generator size.

- Gas-fired, engine-driven or absorption chillers are an effective means for reducing peak electrical demands, Engine chillers, by virtue of higher efficiency at comparable cost, are the more cost-effective alternative.

Comparisons Among Building Types

Comparing the building types, the savings potential shown for retail buildings is dominated by the prototype system configuration and lighting power density. Because most of the building area is served by distributed, individual split-system AC units, few of the measures applied to the central systems (where alternative technologies exist) could have a large impact. Lighting, should be the overwhelming concern for retail buildings. Careful tradeoffs between the store marketing strategy, the cost of more efficient lighting vs. high operating costs of standard lighting, and the quality of light produced, all have to be made. Hotel performance seems most influenced by its 24-hour schedule, and especially the constant operation of the AC system. Air-conditioning conservation measures applied to the hotel prototype had relatively large impacts. Office performance is balanced between internal and external influences, especially lighting and transmitted solar radiation. The office prototype was equally responsive to both architectural and air-conditioning conservation treatments.

Table 3A.
Installed Commercial Building Air-Conditioning Over 100 Tons* in Thailand up to 1986

	Whole Kingdom										Bangkok				
Type	# of Bldgs	% Bldgs ACWC	% Bldgs DX	% Bldgs WCWC	% Tons ACWC	% Tons DX	% Tons WCWC	Total Tons	Average Tons	% of WK Tons	# of Bldgs	Total Tons	Average Tons	% of Bkk Tons	% of WK Tons
Office	129	11%	13%	76%	4%	14%	82%	81292	630	32%	115	77003	670	38%	30%
Hotel	144	8%	1%	92%	3%	3%	94%	71626	497	28%	64	48190	753	23%	19%
Shopping Center	51	8%	6%	86%	1%	2%	97%	54491	1068	21%	46	53093	1154	26%	21%
Movie Theater	240	1%	94%	5%	1%	88%	11%	25523	106	10%	84	10320	123	5%	4%
Hospital	27	11%	0%	89%	8%	0%	92%	12830	475	5%	22	9710	441	5%	4%
Academic	24	17%	4%	79%	4%	4%	92%	8077	337	3%	18	6824	379	3%	3%
TOTAL or AVERAGE	615	8%	22%	70%	3%	10%	87%	253839	413	100%	349	205140	588	100%	81%
TOTAL of Office, Hotel, & Shopping Center	324	9%	6%	85%	3%	7%	90%	207409	640	83%	225	178286	792	87%	70%

* Except for Movie Theaters outside of Bangkok where buildings with 50 tons and above are included.

Source: MITR Technical Consultants, Co., Ltd., Bangkok, Thailand.

Table 3B.
Characteristics of Thai Office Prototype

Gross Floor Area	7869 m^2
Conditioned Floor Area	6439 m^2
Nr. of Stories	12
Aspect Ratio	1:1
Wall Construction	Reinforced Concrete w/ Brick Infil
Window-to-Wall Ratio	.5
Glazing Type	Single-Pane, Tinted, Reflective Bronze (SC = .34)
Occupancy	Perimeter: 14 m^2/person Core: 6.5 m^2/person
Occupied Hours	Mon-Fri: 8am-5pm; Sat: 8am-noon
Lighting Power Density	24 W/m^2
HVAC System	Constant Volume, Distributed AHU
Thermostat Setting	24 °C
Supply Fan Capacity	58228 lit/sec
Outside Air Quantity	9 lit/sec/person
Cooling Plant	2 130-ton Centrifugal Chillers Cooling Tower
Chiller COP	4.0

Table 3C.
Characteristics of Thai Hotel Prototype

Floor Area	20628 m^2
Nr. of Stories	Public Floors: 2 Guest Floors: 10
Nr. of Guest Rooms	280
Aspect Ratio	2.8:1
Wall Construction	Reinforced Concrete
Window-to-Wall Ratio	.4
Glazing Type	Single-Pane, Tinted Blue (SC = .4)
Occupancy	2300 (maximum)
Occupied Period	24 Hours
Lighting Power Density	Public Area: 37 W/m^2 (average) Guest Area: 10 W/m^2
HVAC System	Public Areas: Constant Volume Guest Rooms: Two-Pipe Fan Coil
Thermostat Setting	24 °C
Fan Capacity	154485 lit/sec
Outside Air Quantity	12 lit/sec/person
Cooling Plant	650-ton Centrifugal Chiller, Cooling Tower
Chiller COP	4.0

Table 3D.
Characteristics of Thai Retail Building Prototype

Floor Area	8062 m^2
Nr. of Stories	4
Aspect Ratio	2.5:1
Wall Construction	Reinforced Concrete
Window-to-Wall Ratio	.35
Glazing Type	Single-Pane, Tinted Grey (SC = .63)
Occupancy	18.5 m^2/person
Occupied Hours	10am-7pm
Lighting Power Density	Circulation: 22 W/m^2 Shops: 74 W/m^2
HVAC System	Circulation: Constant Volume Shops: Split-Systems
Thermostat Setting	25 °C
Supply Fan Capacity	13152 (Circulation)
Outside Air Quantity	12 lit/sec/person
Cooling Plant	2 100-ton Reciprocating Chillers Cooling Tower 144 tons (total) Split-system units
Chiller COP	3.4

Table 3E.
Thermal Cool Storage in Thai Office Prototype

	Units	Base Case	Partial Storage	Full Storage	Demand-Limited Storage
Storage Size	ton-hours	-	1200	2667	2208
Chiller Size	tons	260	133	260	225
Cooling Electricity	MWh	598	635	625	628
Total Electricity	MWh	2024	2061	2051	2054
Peak Demand	kW	706	577	478	444
Electricity Cost	k$	101	103	103	103
Demand Cost	k$	75	63	52	49
Storage Cost	k$	-	90	200	166
Chiller Cost Savings	k$	-	51	0	14
Operating Cost Savings	k$	-	9	21	24
Simple Payback	years	-	4.3	9.5	6.3
Cost/Avoided Peak Elec.	$/kW	-	302	877	580

Table 3F.
Thermal Cool Storage in Thai Hotel and Retail Prototypes
(Partial Storage Strategy)

		Hotel		Retail	
	Units	Base	Storage	Base	Storage
Storage Size	ton-hours	-	680	-	1333
Chiller Size	tons	650	450	240	120
Cooling Electricity	MWh	3156	3020	995	949
Total Electricity	MWh	7464	7326	3092	3045
Peak Demand	kW	1393	1223	882	724
Electricity Cost	k$	373	366	154	152
Demand Cost	k$	143	132	94	77
Storage Cost	k$	-	51	-	100
Chiller Cost Savings	k$	-	80	-	42
Operating Cost Savings	k$	-	17	-	19
Simple Payback	years	-	0	-	3.1
Cost/Avoided Peak Elec.	$/kW	-	-171	-	367

Table 3G.
Cogeneration in Thai Office Prototype

Capacity (kW)	Operating Mode	Capacity Factor	Electricity Generated (MWh)	Electricity Sold (MWh)	Operating Cost (k$)	Revenues (k$)	Net Savings (k$)	Payback (years)
300	Therm.	.52	334	0	122	0	54	5.6
	Elec.	.79	1007	0	91	0	85	3.5
	Max.	.95	2434	1404	138	122	160	1.9
400	Therm.	.58	357	0	118	0	58	6.9
	Elec.	.77	1274	0	78	0	98	4.1
	Max.	.95	3310	2011	146	175	205	2.0
500	Therm.	.40	303	0	124	0	52	9.6
	Elec.	.77	1485	0	66	0	110	4.5
	Max.	.95	4138	2628	156	229	249	2.0
600	Therm.	.27	244	0	130	0	46	13.0
	Elec.	.70	1519	0	67	0	109	5.5
	Max.	.95	4868	3314	175	288	289	2.1
700	Therm.	.15	152	0	140	0	36	19.4
	Elec.	.59	1519	0	73	0	103	6.8
	Max.	.95	5841	4288	211	373	338	2.1

Table 3H.
Cogeneration & Thermal Storage in Thai Office Prototype

	Units			
Thermal Storage Mode		Partial	Partial	Partial
Cogeneration Mode		Thermal	Electrical	Max. Output
Electricity Generated	MWh	152	1073	2434
Electricity Sold	MWh	0	0	1349
Electricity Bought	MWh	1402	479	467
Natural Gas Bought	MWh	1541	5020	10276
Peak Elec. Demand	kW	462	211	211
Operating Cost	k$	134	89	133
Revenues	k$	0	0	117
Incremental Cost	k$	339	339	339
Simple Payback	years	8.1	3.9	2.1
Cost/Avoided Peak Elec.	$/kW	1400	685	685

Table 3I.
Non-electric Cooling in Thai Commercial Buildings

		Office			Hotel			Retail		
	Units	Base	Engine	Absorption	Base	Engine	Absorption	Base	Engine	Absorption
Chiller Size	tons	260	260	260	650	650	650	240	240	240
Cooling Energy	MWh	598	1475	2229	3157	7123	11384	995	1921	2981
Total Electricity	MWh	2024	1536	1559	7465	5067	5230	3092	2117	2288
Peak Demand	kW	706	476	484	1393	845	863	882	586	625
Total Gas	MWh	0	1366	2096	0	6364	10463	0	1901	2790
Electricity Cost	k$	101	77	78	373	253	261	155	106	114
Demand Cost	k$	75	52	53	143	93	95	94	64	69
Gas Cost	k$	0	12	18	0	54	89	0	16	24
Total Energy Cost	k$	176	141	149	516	400	445	249	186	207
Chiller Cost	k$	104	182	182	260	455	455	84	168	168
Incremental Chiller Cost	k$	-	78	78	-	195	195	-	84	84
Operating Cost Savings	k$	-	35	27	-	116	71	-	63	42
Simple Payback	years	-	2.2	2.9	-	1.7	2.7	-	1.3	2.0
Cost/Avoided Peak Elec.	$/kW	-	339	351	-	356	368	-	284	327

Table 3J.
High-Efficiency Cases of Thai Commercial Buildings

					Incl. HVAC Credit		
	Units	Office	Hotel	Retail	Office	Hotel	Retail
Energy Savings	kWh / m^2 / yr	141	185	192	141	185	192
Peak Savings	W / m^2	48	34	57	48	34	57
Operating Cost Savings	\$ / m^2 / yr	12	13	16	12	13	16
Incremental Cost	\$ / m^2	24	29	26	11	18	22
Cost of Conserved Energy	\$ / kWh	.016	.015	.013	.008	.009	.011
Cost/Avoided Peak Power	\$ / kW	508	849	453	241	539	384
Simple Payback	years	2.0	2.3	1.7	.9	1.4	1.4
Internal Rate of Return	%	51%	44%	60%	107%	70%	71%

Table 3K.
Criteria of Thai Energy Standard for New Commercial Buildings †

Criteria	Units	Offices		Hotel		Retail	
Lighting	W / m^2	16	(24)	15* 20-17**	(10)* (37)**	23	(25)
Thermostat Setting	°C	24	(24)	24	(24)	24	(25)
Cooling Equipment COP							
--Centrifugal Chillers	-	4.5	(4.0)	4.5	(4.0)	-	-
--Reciprocating Chillers	-	-	-	-	-	3.8	(3.4)
OTTV:	W / m^2	45	(67)	45	(65)	42	(74)
U_w	W / m^2–°C	1.5	(3)	1.5	(2.8)	1.5	(2.8)
WWR	-	.4	(.5)	.4	(.4)	.35	(.35)
SC	-	.3	(.34)	.3	(.4)	.3	(.63)
U_f	W / m^2–°C	6.3	(6.3)	6.3	(6.3)	6.3	(6.3)

† Values given in parentheses are from the respective base cases.

* Guest rooms.

** Public areas.

Figure 3A.
Thai Office Buildings

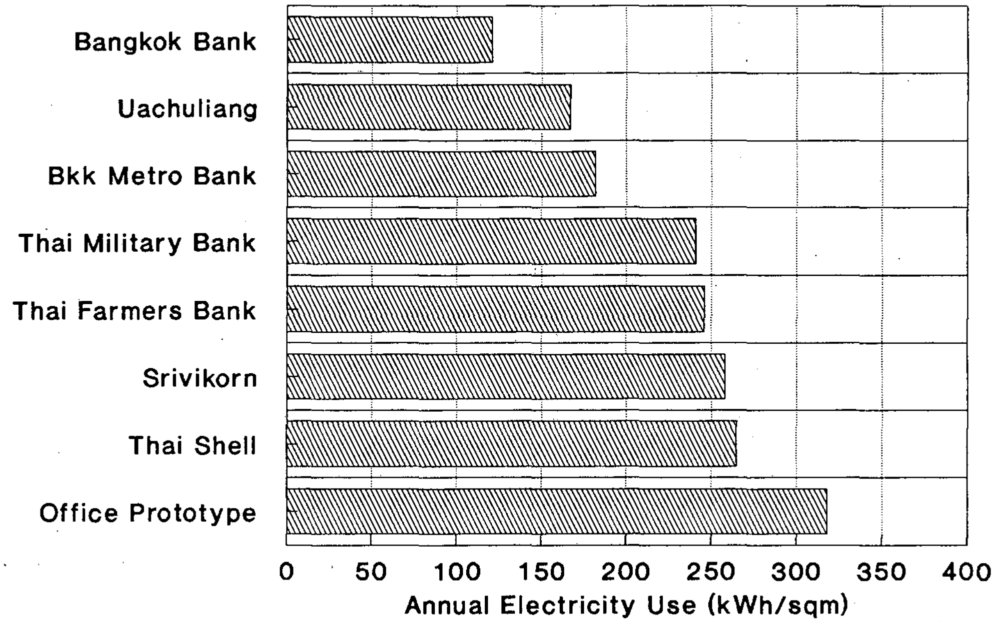


Figure 3B.
End-Use Breakdown of Thai Buildings

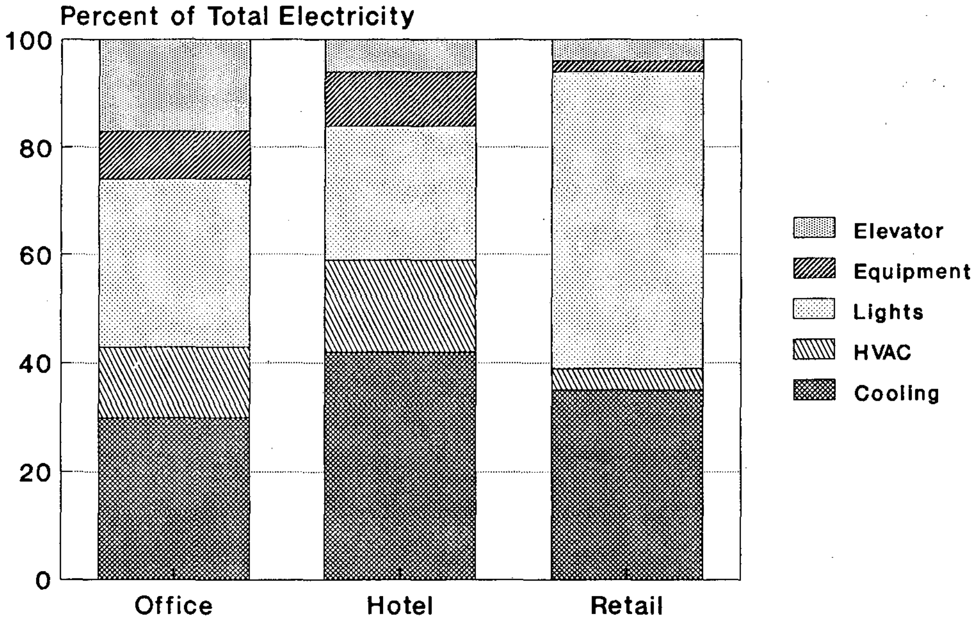


Figure 3C.
Thai Hotels

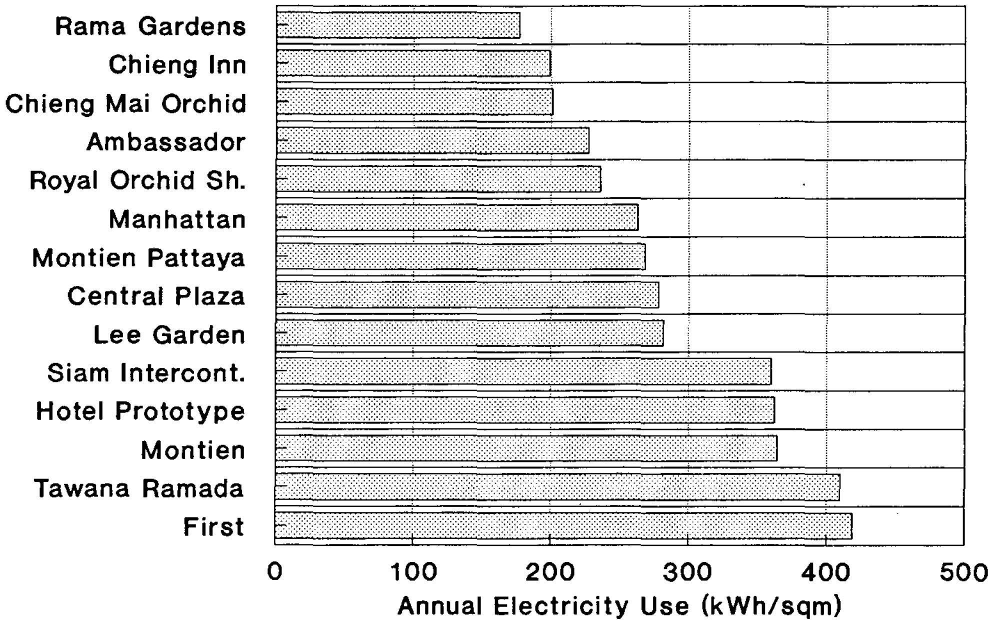


Figure 3D.
Thai Retail Buildings

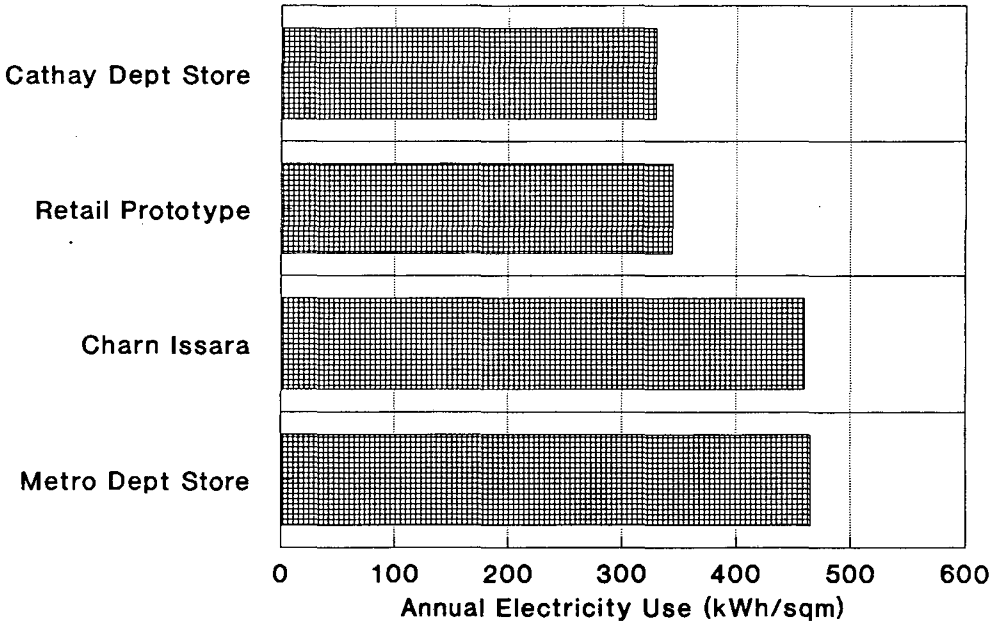


Figure 3E.
Bangkok Weather (1985)

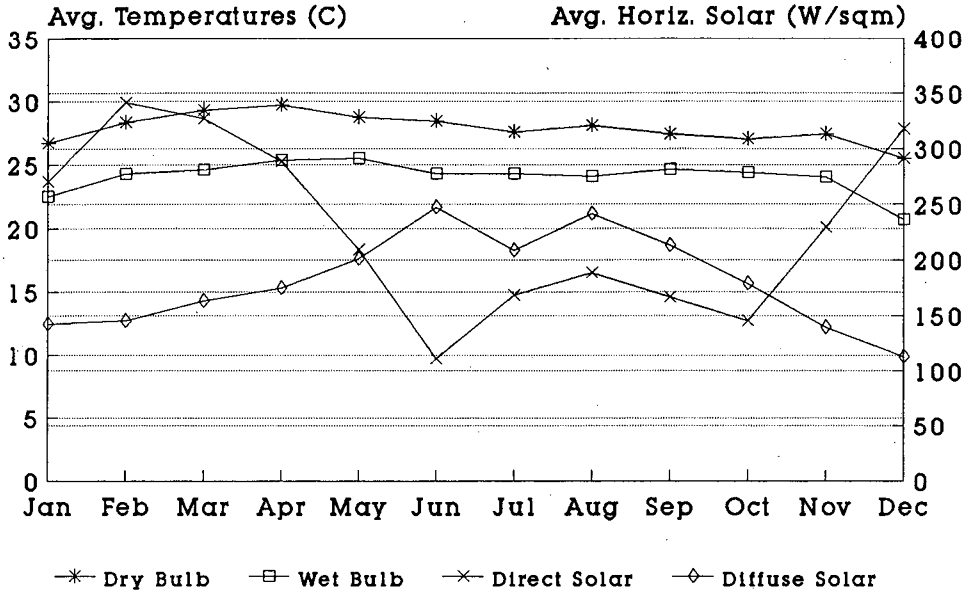


Figure 3F.
Orientation of
Unconditioned Space of Office

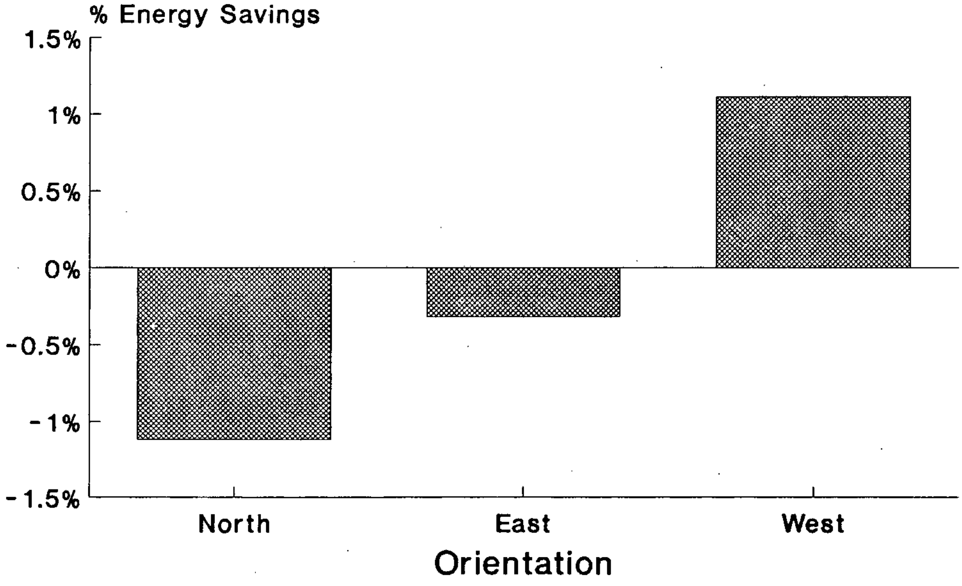


Figure 3G. Infiltration

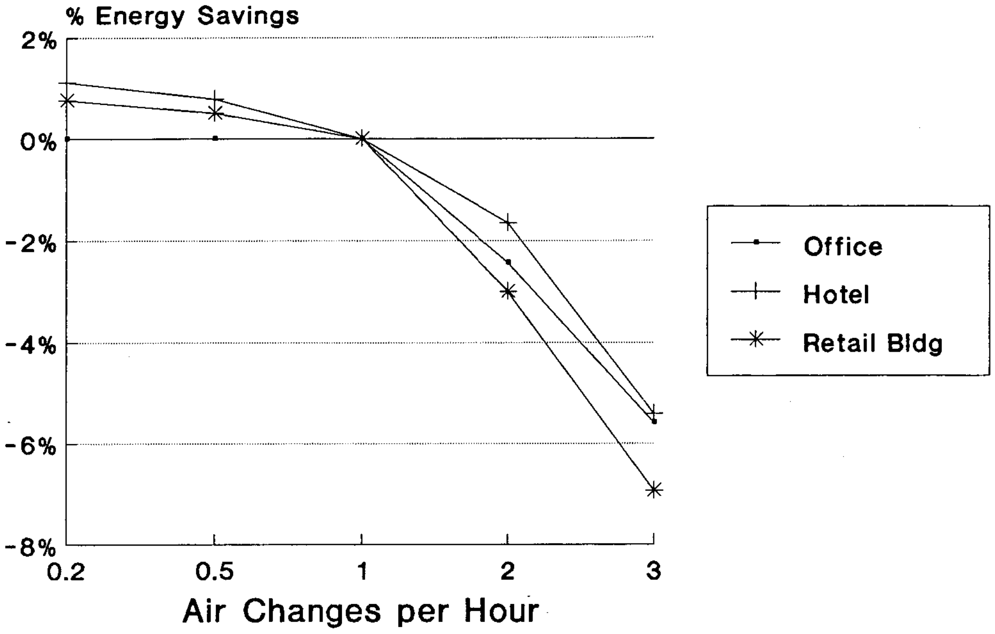


Figure 3H. Thermal Mass

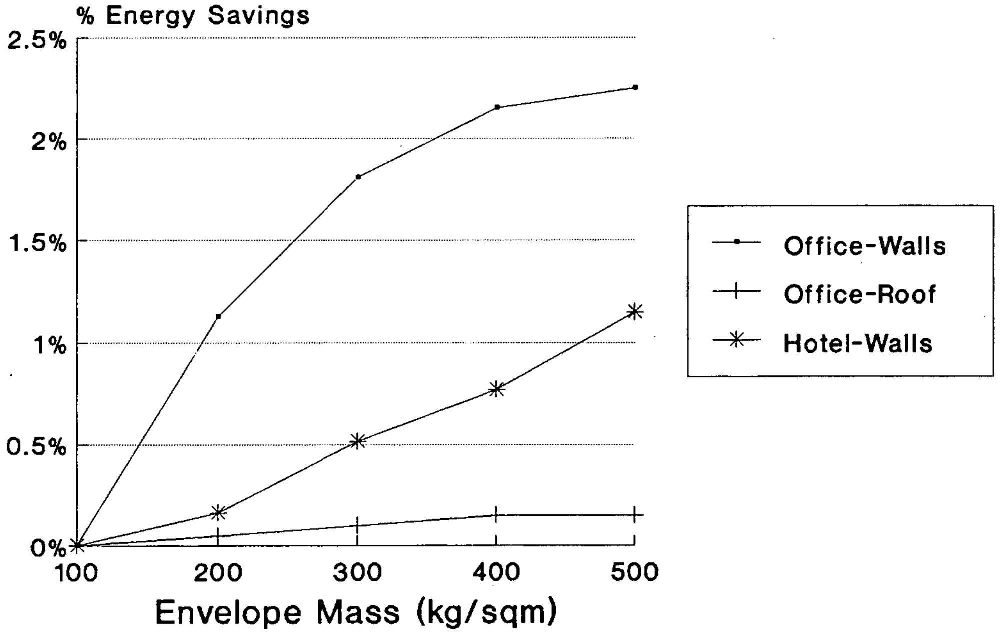


Figure 3I.
Opaque Wall Conductivity

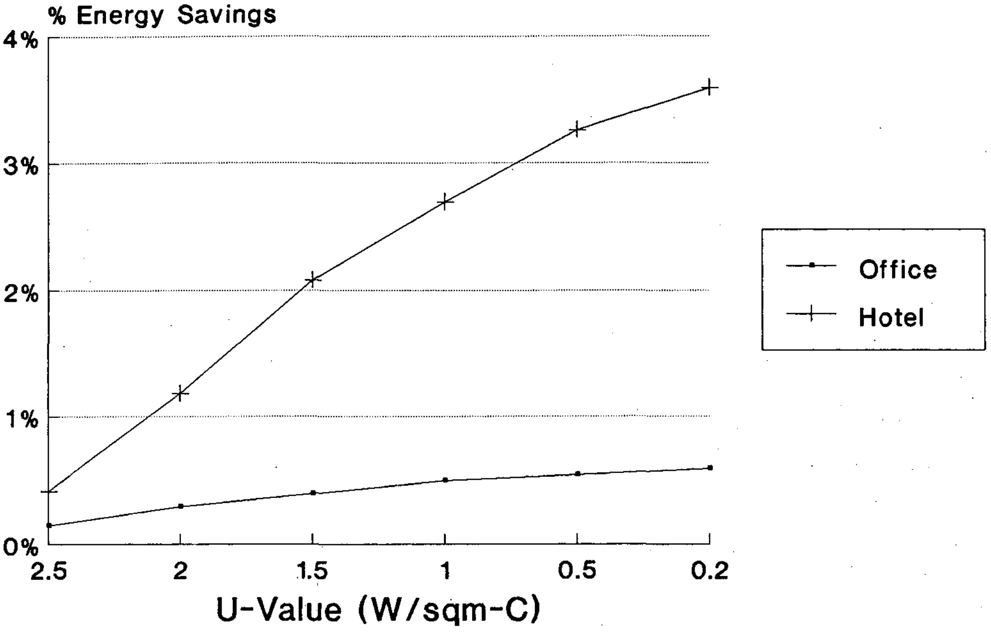


Figure 3J.
Wall Solar Absorptance

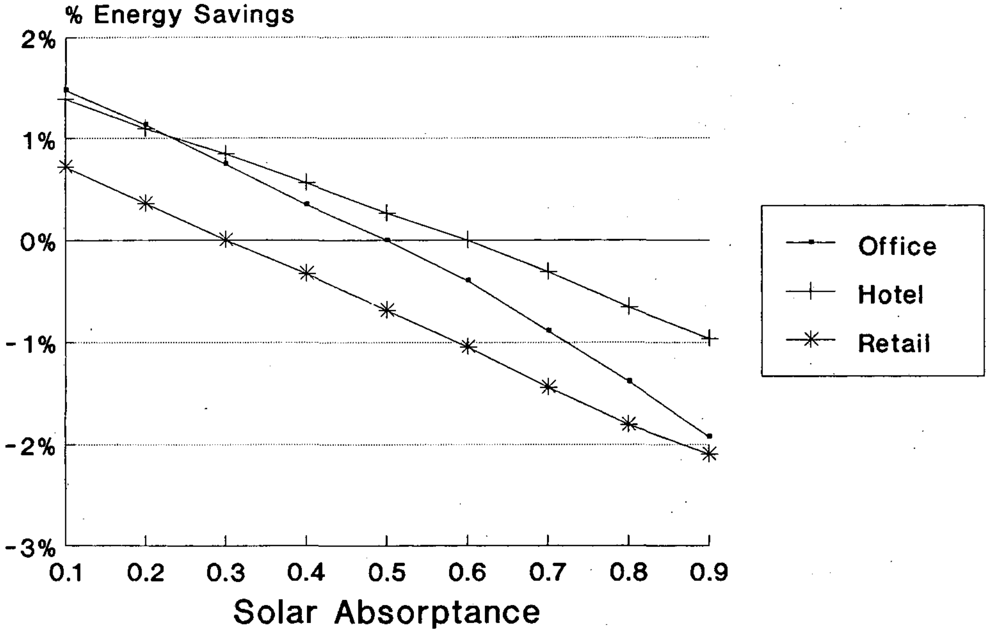


Figure 3K.
Fenestration Area

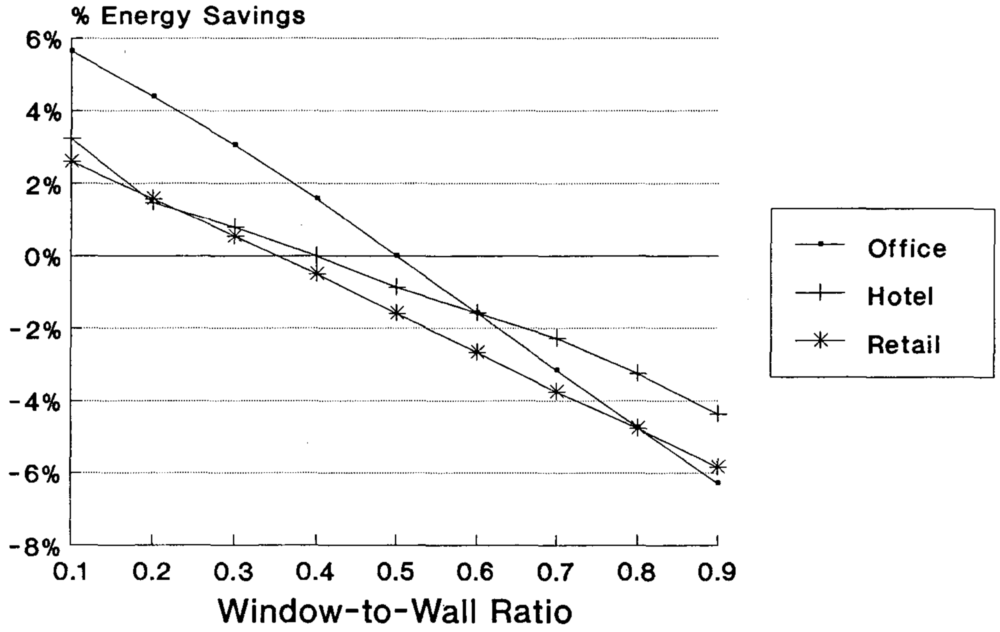


Figure 3L.
Glass Shading Coefficient

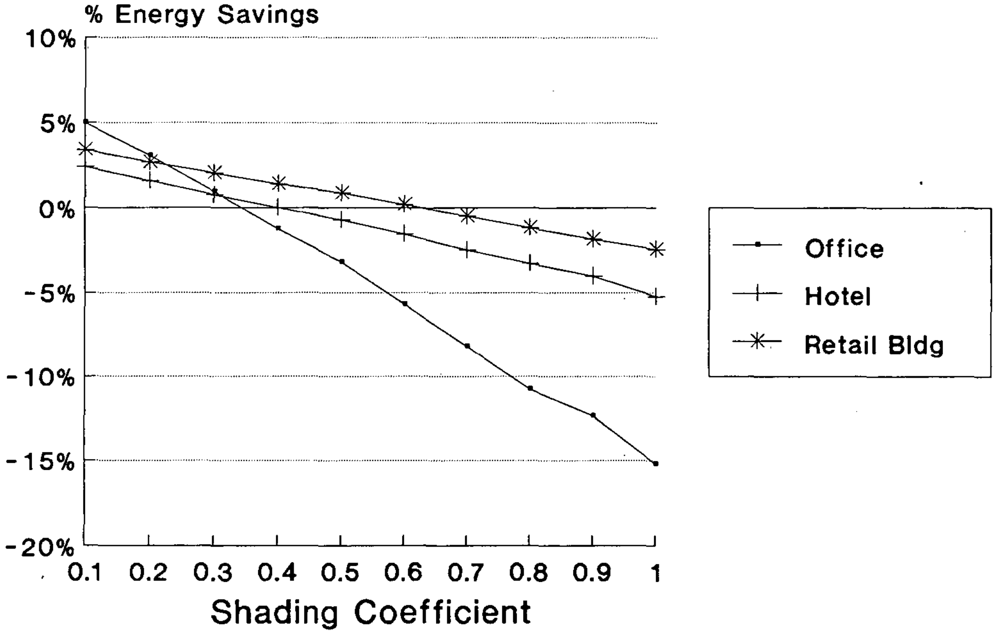


Figure 3M.
External Shading of Office

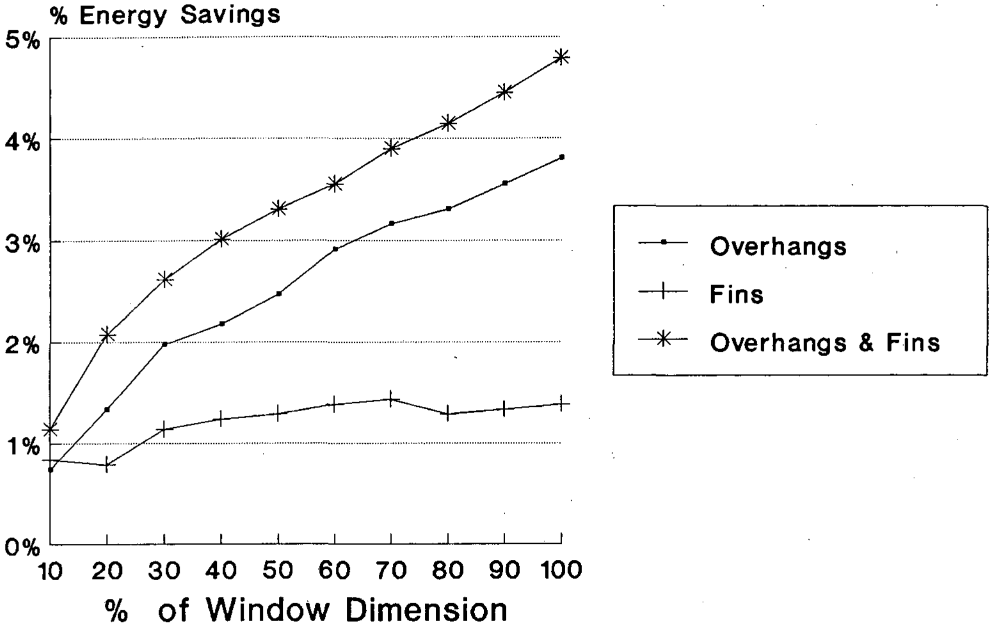


Figure 3N.
External Shading of
Hotel and Retail Building

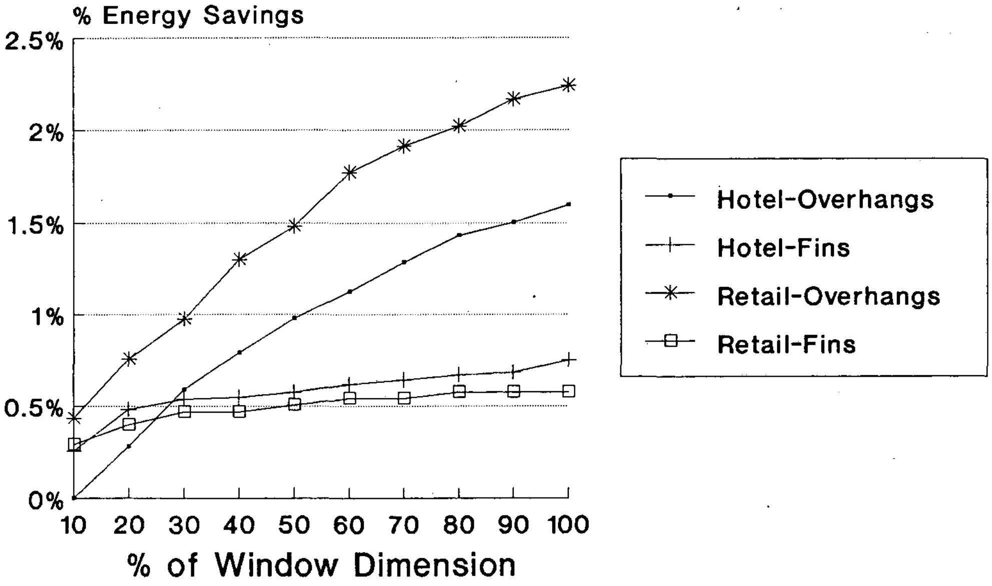


Figure 3O.
Lights and Office Equipment in Offices

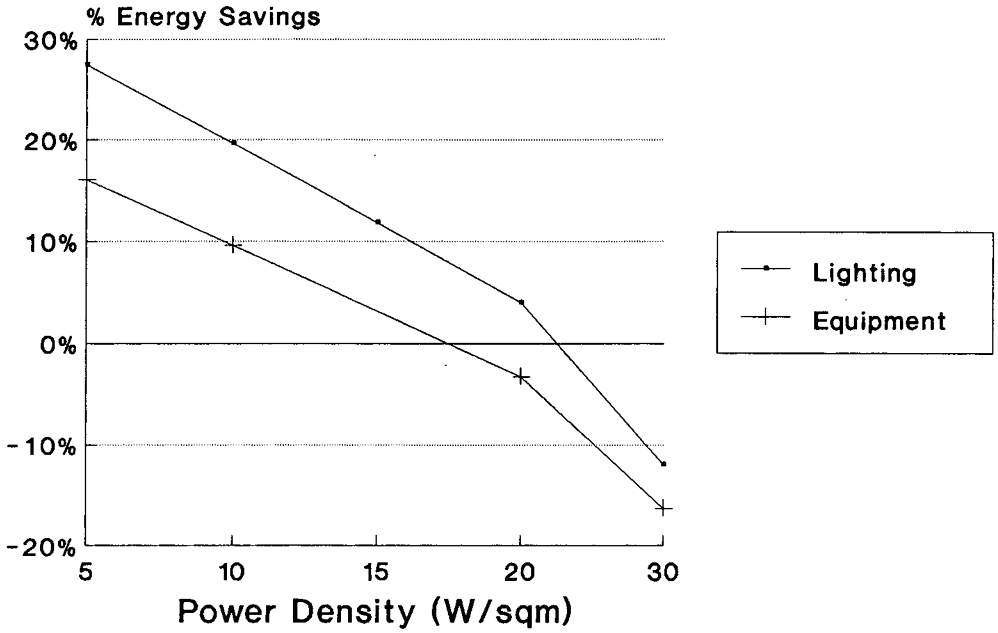


Figure 3P.
Lighting Power Reduction in Hotel and Retail Building

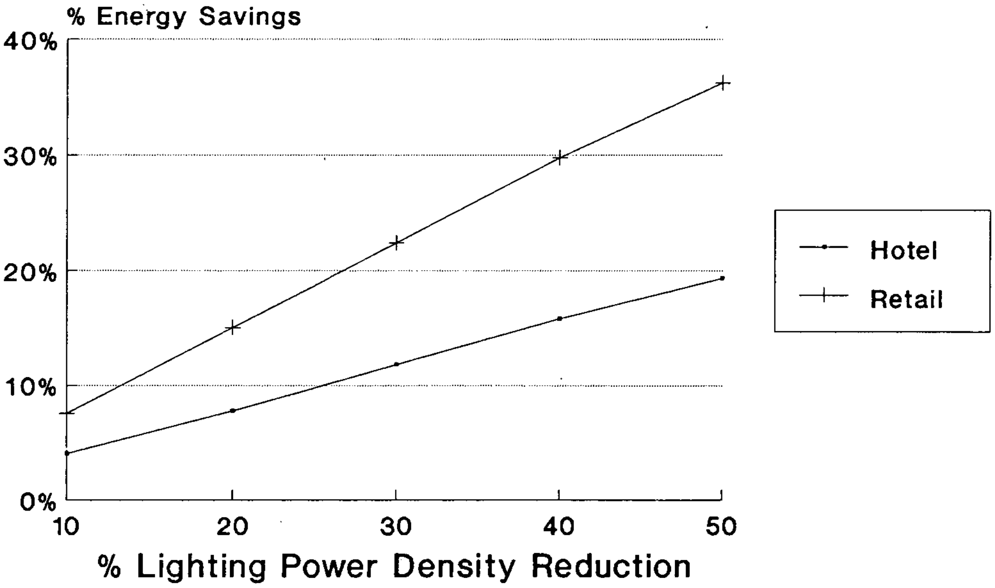


Figure 3Q.
Daylighting in Office Using Stepped Controls

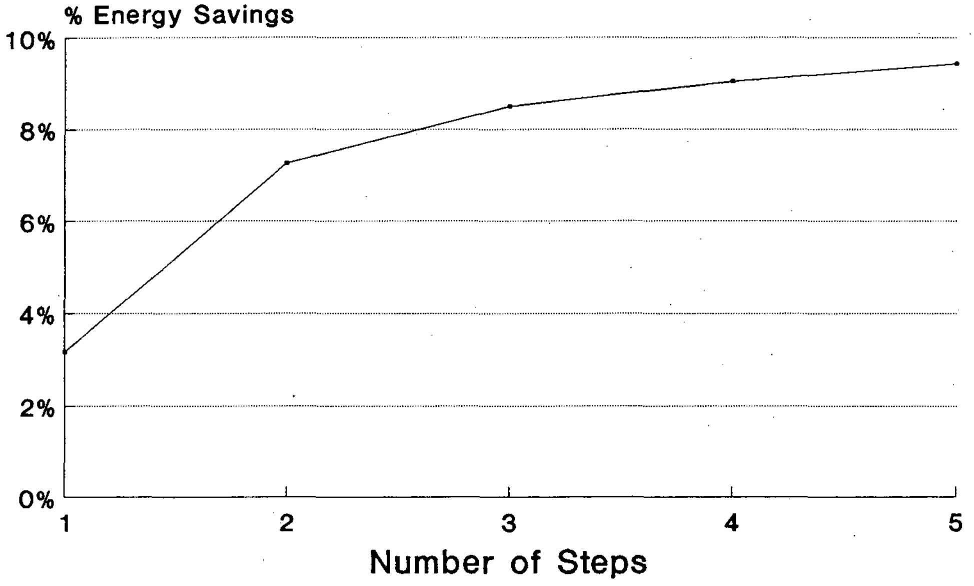


Figure 3R.
Minimum Power Draw of Continuous Dimming Daylighting Controls

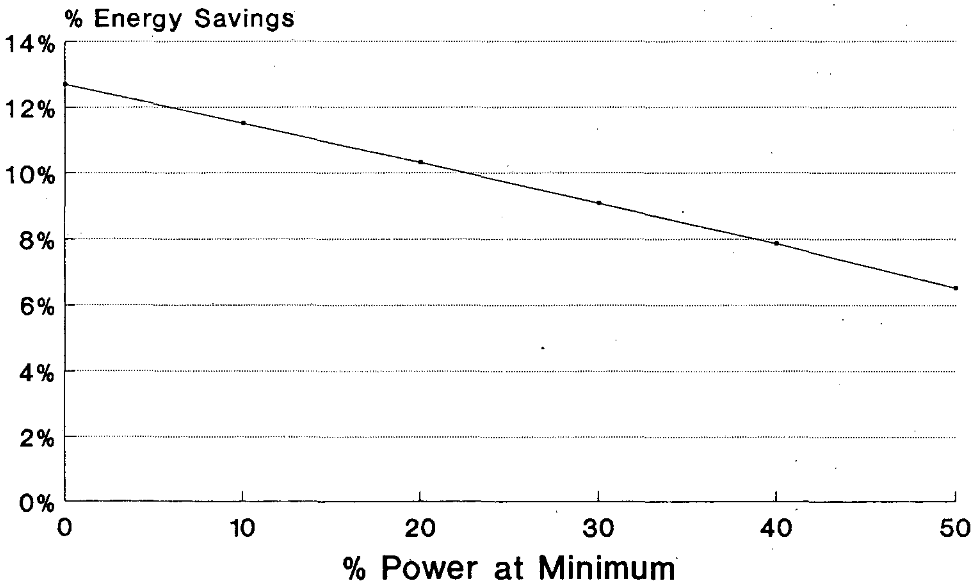


Figure 3S.
Glass Visible Transmittance Effect on Daylighting (SC = .34)

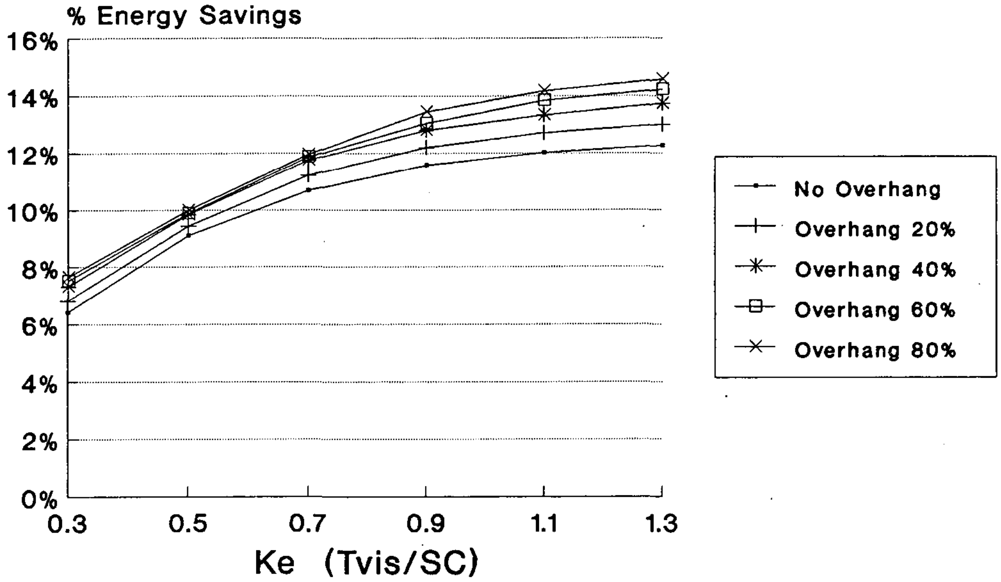


Figure 3T.
Glass Visible Transmittance Effect on Daylighting (SC = .70)

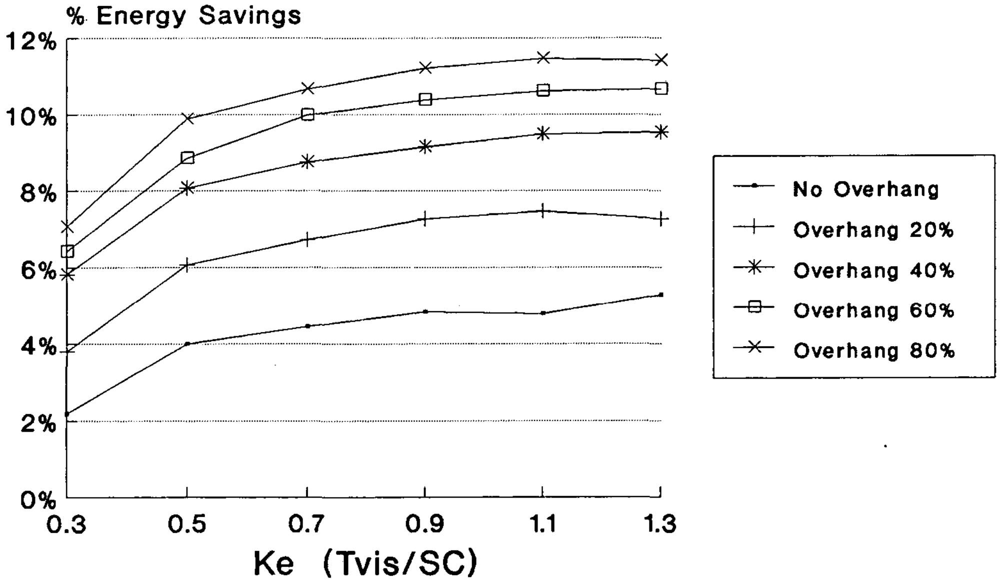


Figure 3U.
Range of Savings for Thai Office Architectural Measures

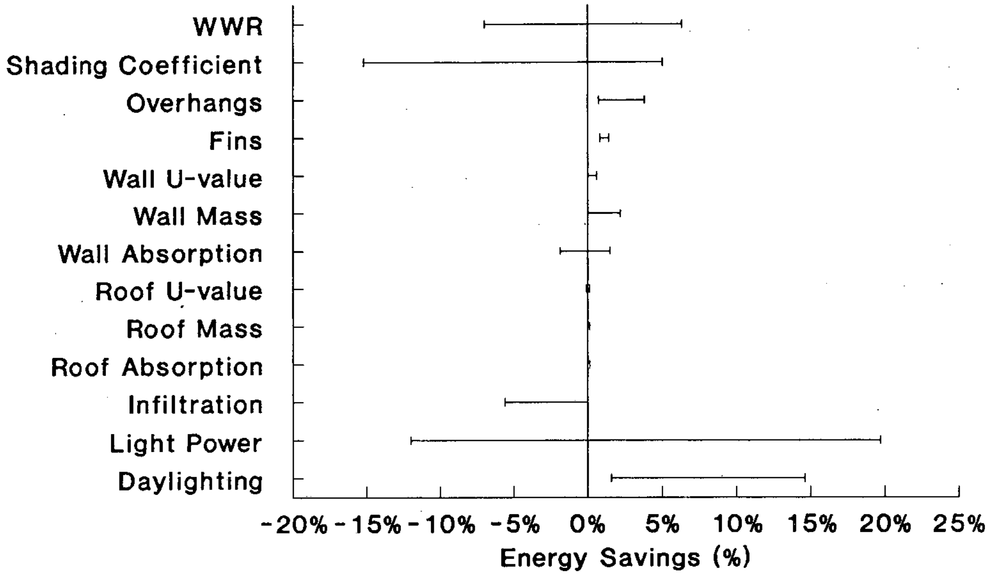


Figure 3V.
Range of Savings for Thai Hotel Architectural Measures

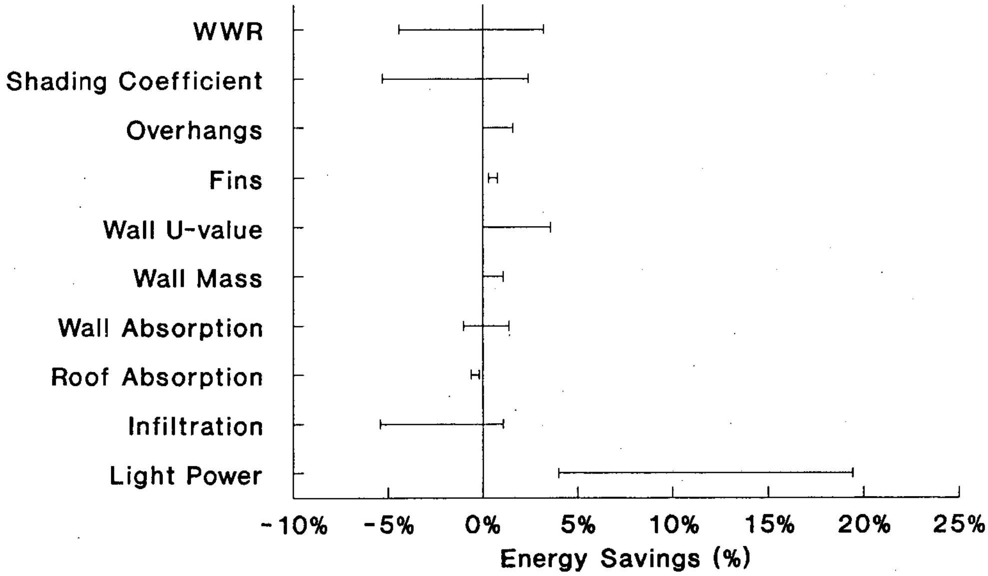


Figure 3W.
Range of Savings for Thai Retail Architectural Measures

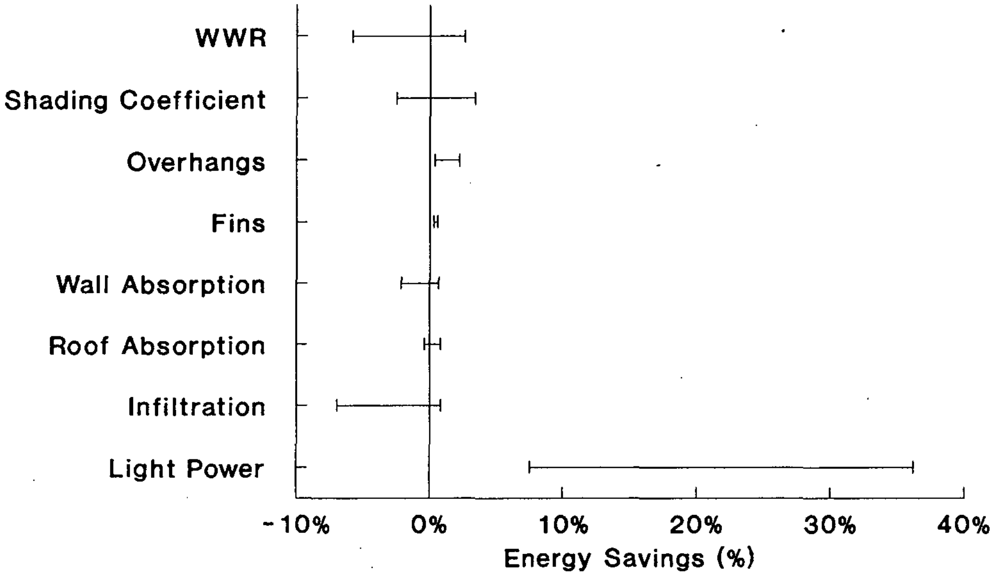


Figure 3X.
Zone Temperature Setting

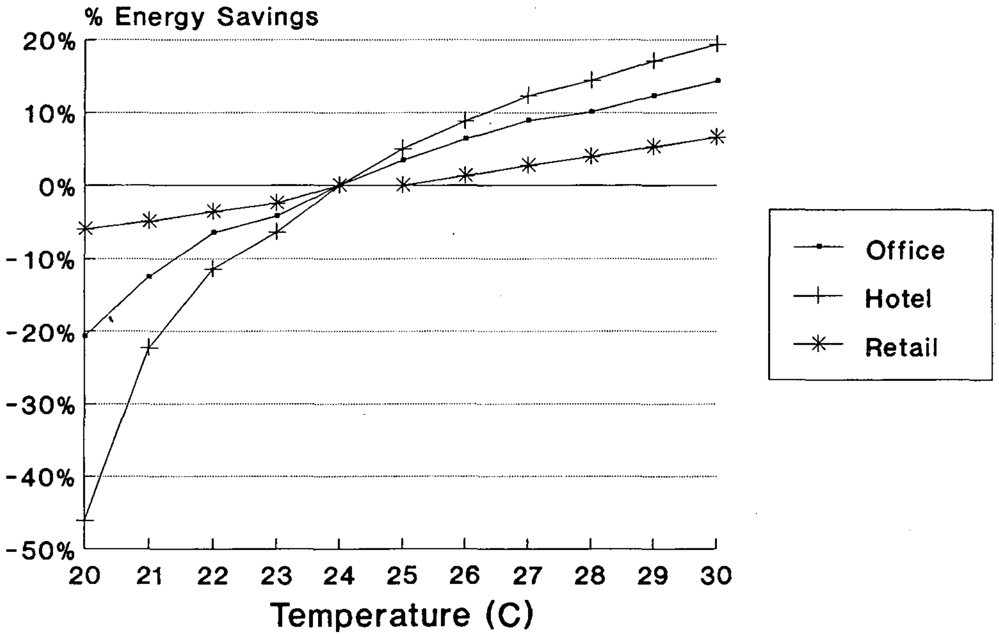


Figure 3Y.
Supply Air Temperature

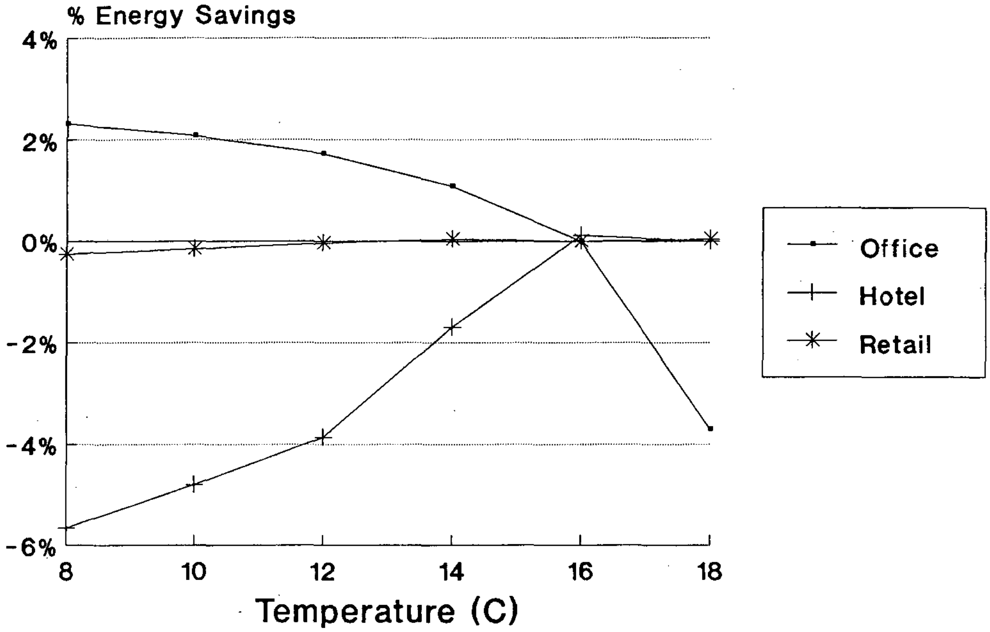


Figure 3Z.
Fan Control for VAV System

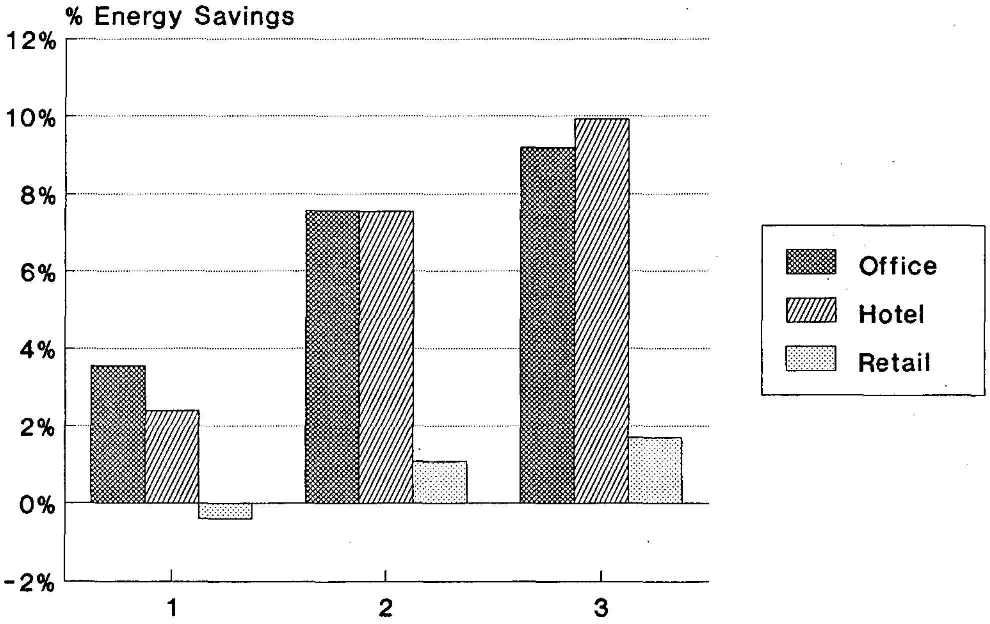


Figure 3AA.
Outdoor Air Quantity

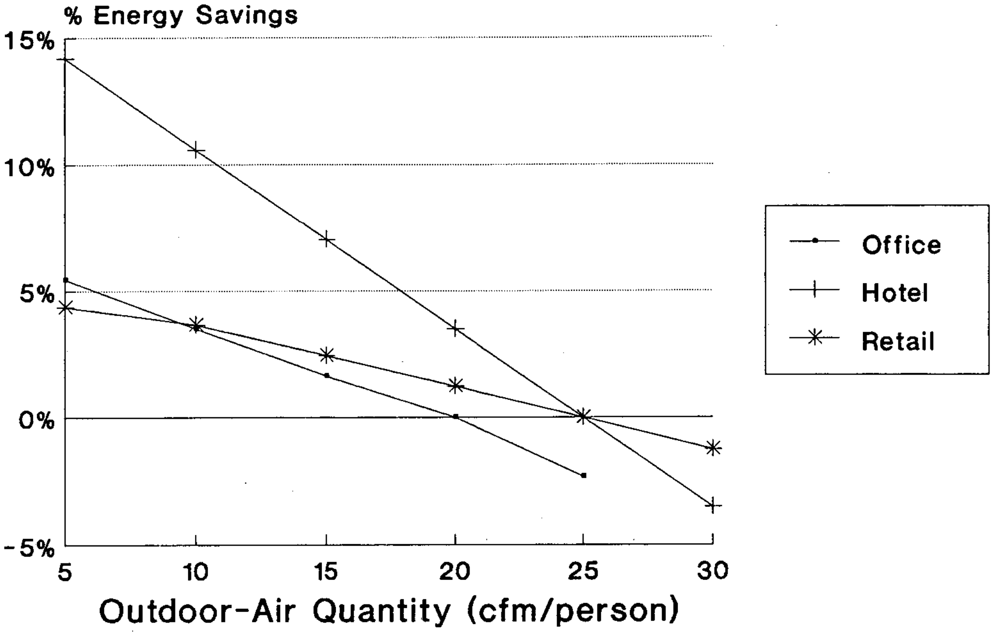


Figure 3AB.
Pre-Cooling of Office

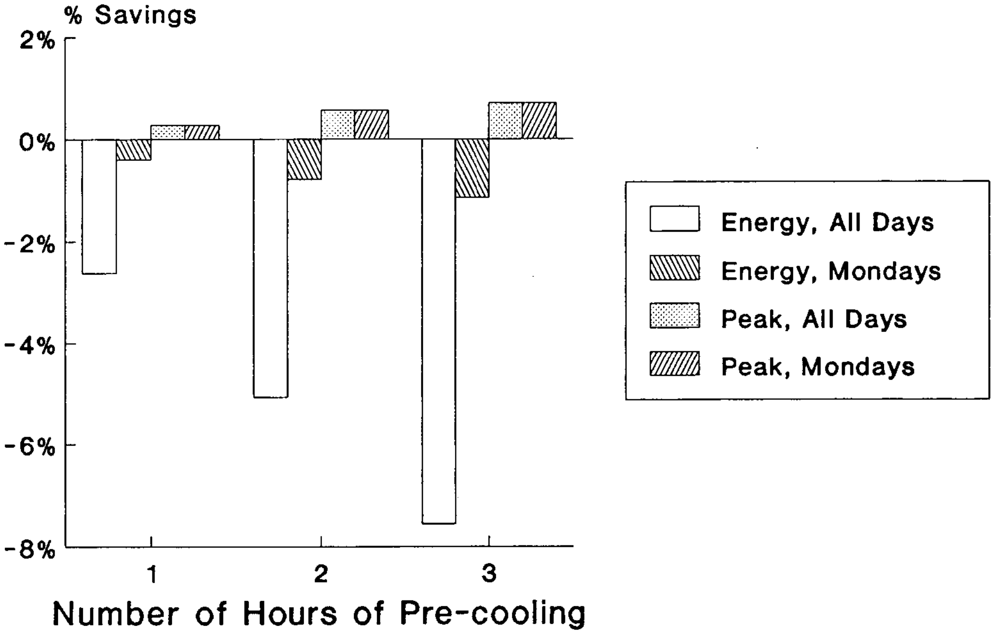


Figure 3AC.
Chiller Efficiency

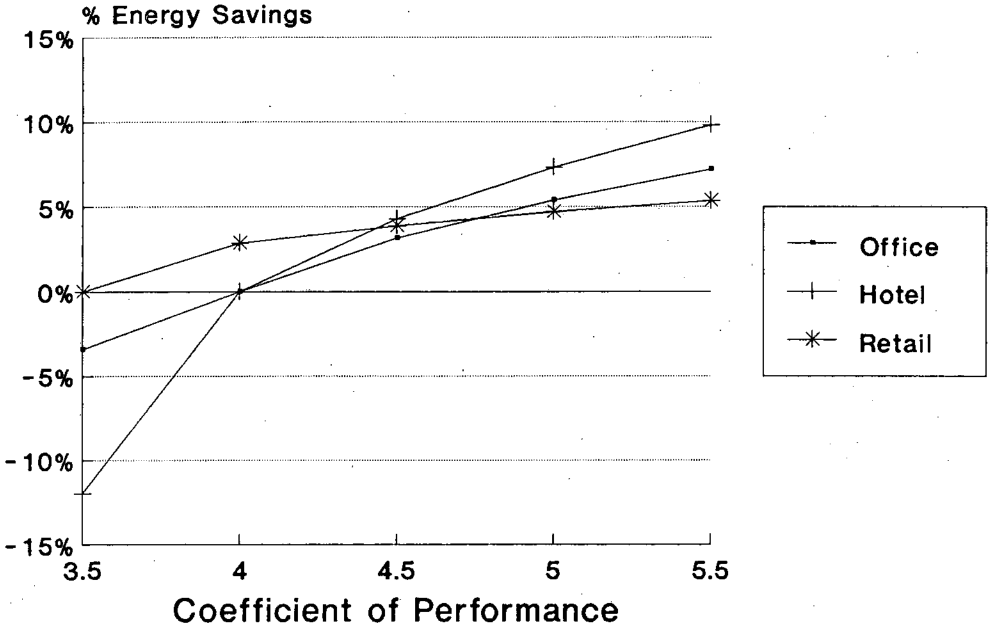


Figure 3AD.
Fan Efficiency

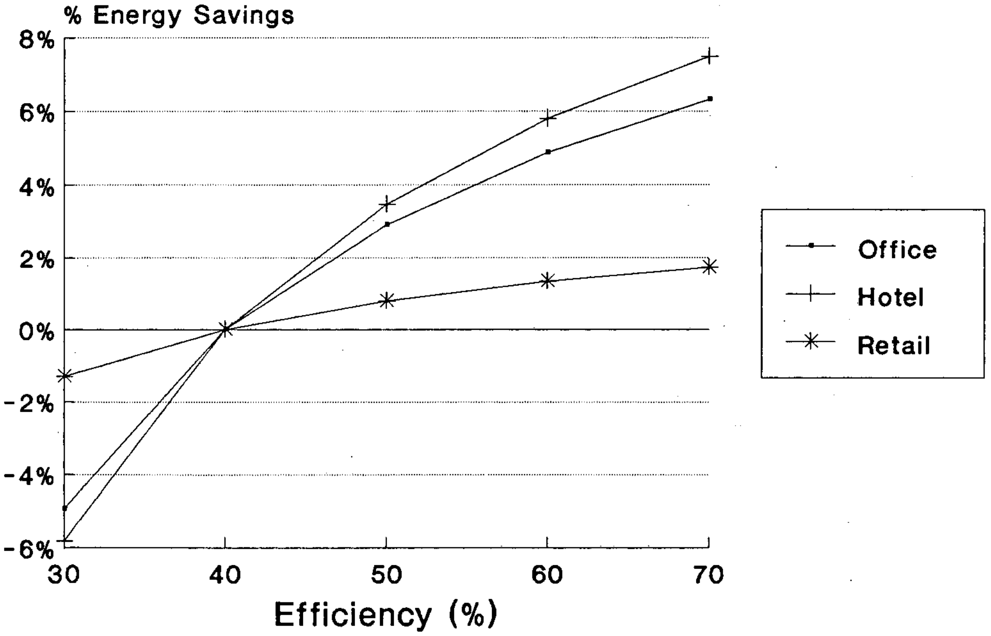


Figure 3AE.
Fan Static Pressure

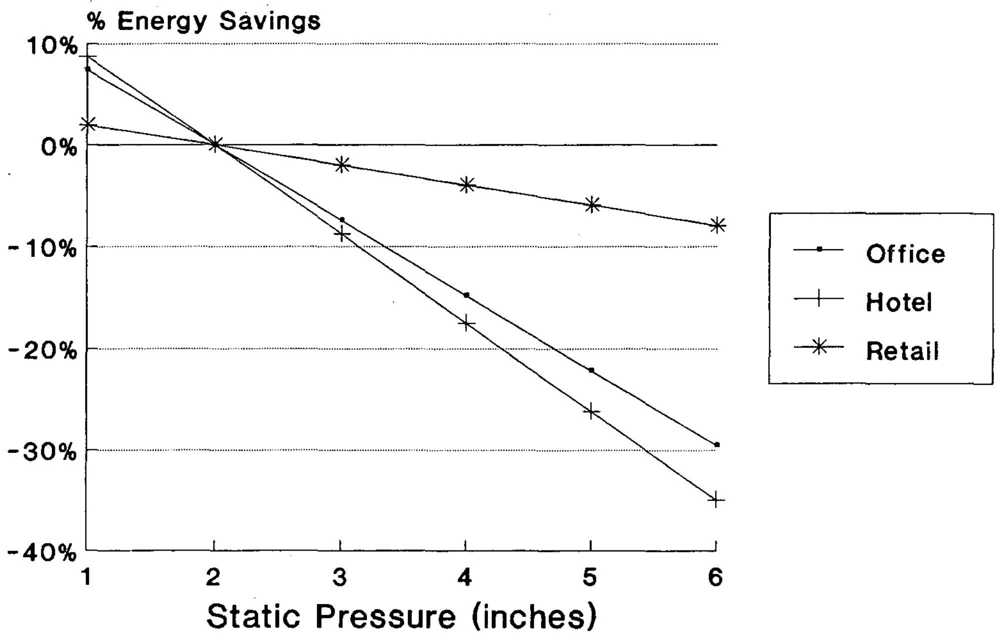


Figure 3AF.
Fan Oversizing Penalty

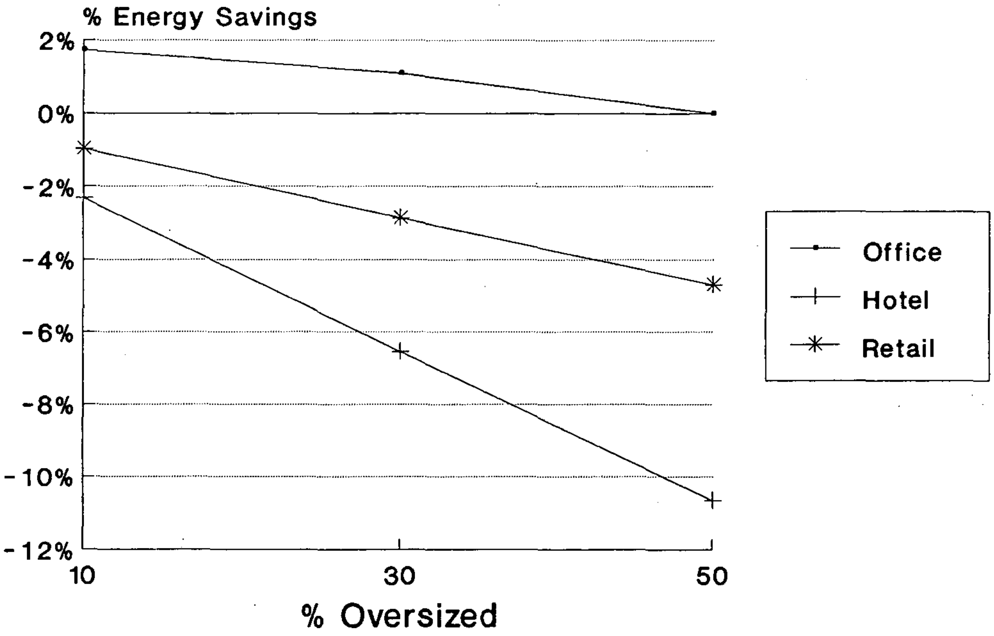


Figure 3AG.
Range of Savings for Thai Office AC Measures

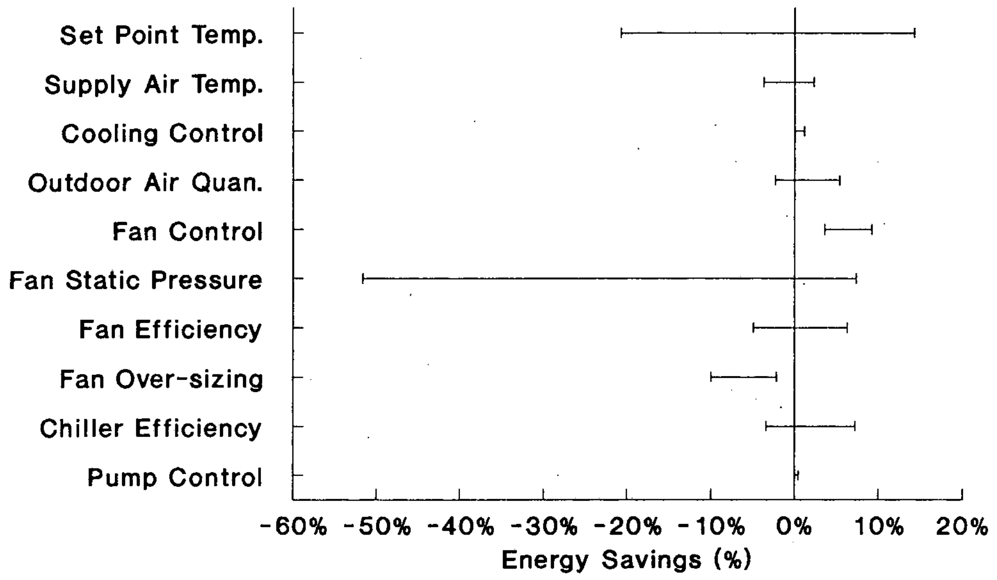


Figure 3AH.
Range of Savings for Thai Hotel AC Measures

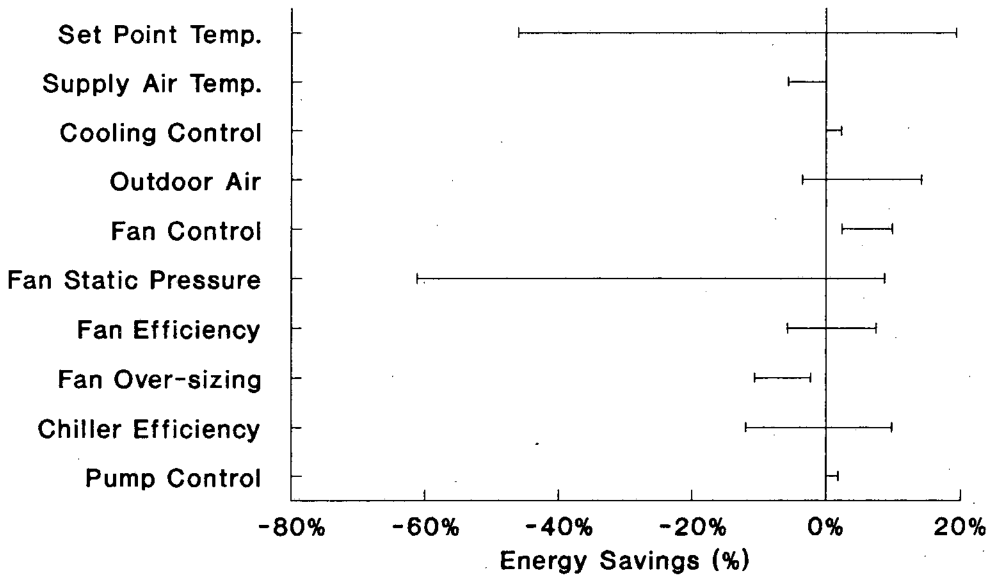
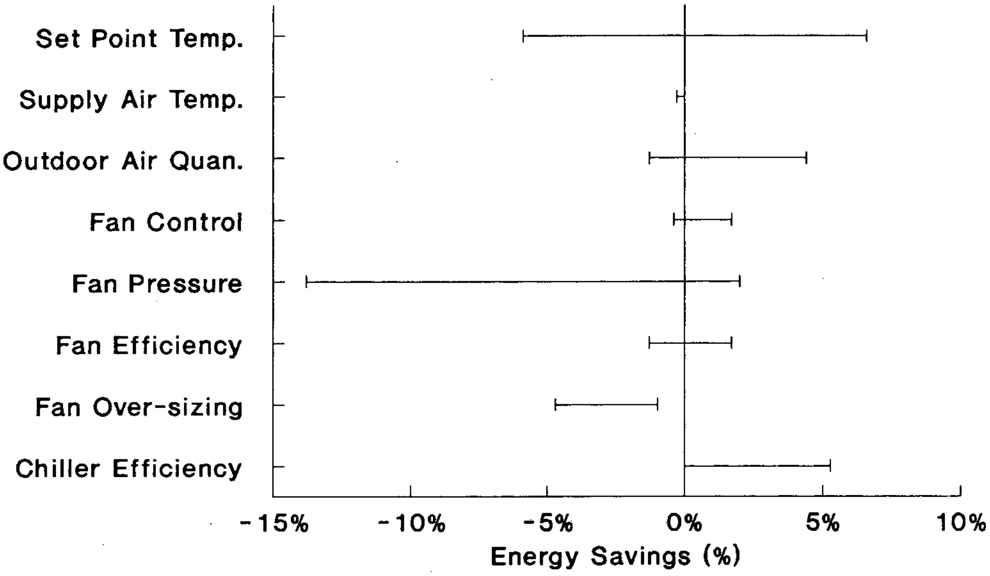


Figure 3AI.
Range of Savings for Thai Retail AC Measures



CHAPTER 4

Impacts on the Thai Electric Utility from Scenarios of Conservation in the Commercial Sector

INTRODUCTION

Conservation measures in prototypical Thai commercial buildings have been shown to save energy in a cost-effective manner. In this chapter we take the analysis a few steps beyond individual buildings to estimate the savings for the commercial sector as a whole, and then project how the Thai electric utility will be affected. It is important to quantify the impacts on the power sector from conservation because of the primacy of electricity in development, because of the large public commitment of capital to the sector, and because utility participation in conservation programs is critical to advancing conservation objectives. Illustrative scenarios of electricity conservation are presented with their resultant impacts on energy demand, operating costs, revenues, and system reliability. Proposed changes to the current Thai capacity expansion plan follow.

The chapter is organized in the following manner. The Thai power system is characterized in terms of its institutional structure, current loads and resources, tariffs, and capacity expansion plan. We then describe how we model the Thai power system and compare our forecast with that of the Thai utility. Next we present our electricity model of the Thai commercial building sector and develop scenarios of conservation using various penetration rates of the technologies. Finally, the impacts of these conservation scenarios on the utility are estimated and discussed.

CHARACTERIZATION OF THAILAND'S POWER SECTOR

Institutional Structure

The Electricity Generating Authority of Thailand (EGAT) is responsible for generating and transmitting power to load centers throughout the entire country. Two agencies are responsible for distributing EGAT power to customers: The Metropolitan Electricity Authority (MEA), which distributes power within the Bangkok metropolis and the Provincial Electricity Authority (PEA), which distributes power "upcountry". Historically Bangkok has consumed more electricity than the rest of the country, but with the emphasis on rural electrification that now reaches 74% of upcountry villages [PEA, 1987], the differences have dramatically narrowed such that by 1989 MEA and PEA each sold equal shares of power. Virtually all electricity is handled through this institutional structure although EGAT does supply a dozen or so large industrial customers directly. Hereafter we refer to this institutional arrangement that produces and delivers electric power to customers collectively as "the utility".

Loads

In 1989 EGAT met a peak demand of 6230 MW while generating 36,566 GWh of electricity. Electricity demand has experienced nothing but fantastic growth, measuring above 10% p.a. over the last decade. Energy and peak demands have grown at virtually the same rate throughout, resulting in a load factor[1], a measure of the diversity of the loads, consistently in the

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[1] Defined as the ratio of total electricity generated in a period to the product of peak demand and

range of 67-68%. Figure 4A shows the hourly system load shapes for a typical and peak day in 1987. Interestingly, the peak day occurs not during the hottest summer months, but six months afterwards in the last month of each fiscal year. This means that overall electricity growth overshadows any seasonality in the occurrence of the system peak. The system peaks at 8 p.m., which suggests a strong residential contribution to the peak. Because Thailand is still generally an agrarian society, the load shape reflects patterns of electricity usage in the home, primarily for lighting, running fans, and cooking rice in the evenings [MEA, 1986]. As Thailand continues to grow economically, the trend of the system load shape should be towards that of Bangkok. Figure 4B also shows the contributions of customer classes to the overall MEA load shape. In contrast to the overall system, the residential sector contributes little to MEA's peak. Commercial and industrial activity exert much more influence over the magnitude and timing of the afternoon peak. This paper focuses on electricity use in large commercial buildings, and so the large business customer class is separated out. The large business class itself has a broad peak between the hours of 11 a.m. and 4 p.m., where air-conditioning is the major factor inducing peak power demand during the period.

Thailand's electricity demand is forecast to grow 8.5% annually, with the peak load growth at 7.9% annually, over the twelve-year period beginning 1990 [LFWG, 1989]. These electricity growth rates are accompanied by optimistic economic expectations of 7% annual GDP growth. Over a shorter five-year time horizon the growth rates are forecast much higher: 11.2% p.a. for both electricity and peak.

The electricity forecast is a cooperative venture between EGAT, MEA, PEA, and other government agencies including the National Energy Administration, the National Economic and Social Development Board, the National Energy Policy Office, and the National Institute for Development Administration, all of whom are coordinated by the Thailand Development Research Institute, a private think-tank. The load forecast is done by customer class for PEA and MEA, respectively, and then consolidated to the EGAT generation requirement including historic loss factors. Peak demand is predicated upon measured daily load curves by customer class for MEA and PEA, forecasts of growth in number of customers in each class, and historical average ratios of EGAT's peak demand to the sum of non-coincident demands of MEA and PEA.

For the residential class, an end-use approach to forecasting electricity use has been adopted. Projecting demand from the various industrial and commercial classes utilizes historic and projected (mostly constant) ratios of energy consumption per unit value-added and forecasts of value-added growth in sub-sectors of each class. For instance, the Large Business Class (>30 kW) is broken down into 1) wholesale and retail trade and transport, 2) banking, insurance, and real estate, 3) hotels and restaurants, 4) other market services, and 5) non-market services. The projected demand of the Large Business category[2], combining both PEA and MEA, grows from 3434 GWh in 1989 to 9626 GWh in 2001, or a 9.8% annual growth rate. In the year 2001, the Large Business loads make up 10% of the total system loads. It is within these growth expectations for the commercial sector that alternative conservation scenarios are analyzed in this paper.

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the total number of hours in that same period or,

$$LF = \frac{\text{Total Generation}}{\text{\# Hours} \times \text{Peak Load}}$$

[2] Including the "Specific Business" class to whom energy price discounts were granted by the Board of Investment as a promotion.

Current Resources

Thailand is blessed with abundant natural resources. In 1989, Thailand was able to generate 88% of its electricity from indigenous sources of primary fuel. These resources include natural gas from the Gulf of Thailand, lignite, a low-grade form of coal, found in deposits both in the North and South, and the surface water run-off of tropical monsoons. To date little in the way of oil resources have been discovered; most oil is imported. In terms of plant capacity, EGAT has installed 2249 MW of hydro, 2847 MW of oil or gas-fired[3] thermal (steam), 760 MW of gas combined-cycle, 238 MW of diesel and gas-turbines, and 1159 MW of lignite thermal plants. These plants are distributed throughout the country, either close to fuel resources or load centers.

Electricity Tariffs

EGAT, as the electricity generating body sells its output to the two distribution authorities, MEA and PEA. Electricity rates are structured such that ultimate customers in a given category in PEA territory pay the same price as those in the MEA service area. Residential and small commercial customers pay on an inclining block scale, which for the former rises from 1 Baht per kWh ($0.04) for the first 5 kWh to 2.43 B/kWh ($0.097) for monthly consumption exceeding 800 kWh. All other categories of customers experience both energy and monthly peak demand charges.

For the Large Business class, the energy charge is 1.23 B/kWh ($0.049) and the demand charge is 229 B/kW ($9.16). Under a new arrangement, the demand charges of large industrial concerns are now adjusted to the time of occurrence using time-of-use (TOU) rates. Under this regime, consumers pay 180 B/kW/month ($7.20) during the peak period 6:30 p.m. to 9:30 p.m., 90 B/kW/month ($3.60) for any excess demand over that of the peak period occurring during the partial peak hours of 8:00 a.m. to 6:30 p.m., and pay no demand charge in the off-peak period. The energy charge of 1.22 B/kWh ($0.049) is unchanged over the day. Previously, large industrial customers had a simple 170 B/kW/month ($6.80) demand charge. There has been discussion about adopting TOU in the commercial sector, but it has not yet been implemented.

Because of the institutional separation of the costs of generation and the cost of serving ultimate customers, and other political considerations, including social equity between the urban rich and the rural poor, and the effect of energy prices on development, class tariffs do not necessarily reflect their marginal costs [World Bank, 1985]. It is apparent that commercial customers, who pay the highest rates in the tariff structure, are subsidizing residential customers. Moreover, there are regional cross-subsidies: i.e., while the cost of supplying the distribution network in Bangkok is lower than doing so upcountry, MEA pays 30% more than PEA for EGAT's electricity [EGAT, 1988],

Capacity Expansion Plan

Because electricity cannot be stored economically, and because of the long lead-times involved in bringing a generating plant into service, electric utilities typically develop formal plans for expanding capacity. In conjunction with the annual load forecasting exercise which invariably alters expectations of future loads, EGAT conducts an evaluation of its plan for future capacity investment. The latest power development plan (PDP) anticipates a threefold increase in Thailand's generating capacity by the year 2006[4], to nearly 23,000 MW [EGAT, 1989]. This

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[3] EGAT has retrofitted many boilers to dual-fuel capability so that it can easily respond to changes in imported oil prices and natural gas availability.

[4] EGAT extended the time horizon of the Load Forecast Working Group's 1989 forecast from 2001 to 2006, though how it did so is left to the reader's imagination.

is in addition to existing plant renovations of 140 MW to hydro and 1568 MW to thermal units, plant retirements of 2930 MW, as well as expansion of the transmission system. Under this plan, Thailand will significantly expand its baseload capacity using indigenous lignite and imported coal. Several new combined cycle plants will come on line early in the 1990s, but after that no new plants using natural gas are planned, apparently due to the uncertainty of supply. Only very modest increases in hydro capacity are shown, no doubt in part because of the politically divisive experience with the proposed Nam Choan dam, whose reservoir would have inundated a large portion of Thailand's greatest wildlife sanctuary and led to the demise of one of of Southeast Asia's largest remaining contiguous rain forests [The Nation 1988; TDRI 1987]. In keeping with past policies, EGAT continues to shy away from plants utilizing imported oil. The nuclear option remains in EGAT's long-term thinking but has not been incorporated into the existing plan.

Planning Method. EGAT employs a capacity expansion model, WIGPLAN, to determine the optimal mix and timing of resource additions [Westinghouse 1984]. The model is used to simulate the system in each month of the planning period to test whether EGAT's reliability criteria are met; in the event that they are not, the model selects the least-cost option from a menu of technologies (input by the user) to satisfy the criteria. The reliability criteria used by EGAT are based upon loss of load probability (LOLP), reserve margin (RM), and loss of the largest generating unit.

LOLP is a measure of the likelihood that the power system's generation capacity will at some time be insufficient to meet load. This concern comes about because power plants occasionally shut down partially or fully without notice, (referred to in the industry as "forced outage") and because of the need for an instantaneous match between power source and load, where any shortfall leads to brown- or black-outs. LOLP is a mathematical construct whereby generating units are treated as independent random variables, the sum of which are compared in a probabilistic manner to the load [Kahn, 1988]. Algorithms for calculating LOLP are a common feature of utility production-cost models, one of which EGAT uses for testing its reliability criteria of one day per year[5].

Reserve margin is a measure of the system's installed excess capacity. It is (expressed in percent),

$$\mathrm{RM} = \frac{\text{Installed Capacity} - \text{Peak Load}}{\text{Peak Load}} \times 100 \tag{4A}$$

It is more straight forward than the LOLP, but at the expense of containing no information about plant performance. RM is related to LOLP in that, for a given system configuration, a given RM will yield a particular LOLP. EGAT states that to maintain the LOLP below one day/year, a RM of 25% is preferred, but that public financial constraints require them to settle for a range of 15-20% [EGAT, 1989].

The last reliability criteria EGAT uses defines firm capacity as the total capacity less the capacity of the two largest generating units and stipulates that firm capacity be greater than the peak load.

Other constraints besides cost and reliability play a role in the ultimate composition of the power development plan. One, mentioned above, is a financial constraint on the amount of foreign borrowing allowed by the government. Another is the availability of fuels for future power plants. Proximity to load centers and/or fuel sources is a consideration as is the policy of

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[5] LOLP, being a dimensionless probability number, is customarily expressed in terms of days/year.

utilizing indigenous resources where possible. All these factors can all sway the plan away from the economic "optimum". While EGAT does take these factors into consideration in making up its capacity expansion plans, to date it has not taken into account the possibility of conservation or load management activities.

MODELING EGAT'S POWER SYSTEM

To properly account for the impact of alternative load scenarios, a model capable of simulating the operation of the present and future Thai power system was employed. The following is a description of the features of the model along with the inputs used in this case study, followed by the calibration of the base case to that of EGAT's, and an examination of the effect of different hydrologic seasons on the results.

Production-Cost Simulation

ELFIN belongs to the class of models that simulate the dispatch of electricity generating plants to meet loads, otherwise known as production-cost models. The dispatch is done in such a way that the economic performance of the overall system is optimized subject to some important constraints (see below). The results that ELFIN provides includes the level of generation of each plant, primary fuel consumption, marginal and total production costs, and overall system reliability (via LOLP). The section that follows draws heavily on the paper by EDF [1988].

Load Shapes and Modifications. The program relies on load shapes, ideally in the form of chronological hourly loads over a typical week, the week representing one of each month or several months. These hourly loads are then used in a relative sense (i.e. as a "shape") to scale up to the forecast annual peak and energy consumption values in different years. In each year ELFIN "raises" the input shape to match the input value for peak, and then "rotates" the shape about the peak to match the area under the shape to the input energy total. The loads once scaled can then be modified chronologically to represent the effect of a time-varying "resource" such as a conservation program.

Maintenance Scheduling. Maintenance outage can be explicitly scheduled, or can be simulated using the model's distributed maintenance scheduling feature whereby, on the basis of an input annual plant maintenance rate, the model chooses the week(s) in order to levelize as much as possible the reserve margin among typical weeks. Whichever method is used, a given plant's capacity is de-rated by the amount of the apportioned maintenance rate to account for the time the plant is out of service.

Dispatch Order. ELFIN sets up a precedence for dispatching units based on economic order and operating constraints. The constraints, which shift the model results away from the economic optimum but in so doing better represent actual utility operations, include must-run plants that meet local reliability or voltage needs, committed slow-start units, and the run-of-river portion of hydro power plants. Once the constraints are honored, then plants are dispatched in economic order by variable cost.

Probabilistic Dispatch. Perhaps the key feature of production-cost models like ELFIN is that they are able to take random (or "forced" or non-scheduled) outages of generating plants into account to arrive at an expected value of production, and hence costs. The method used is called the "equivalent remaining load duration curve method," or sometimes referred to as the Baleriaux-Booth method after the originators. The most lucid general description of the technique comes from EDF [1988].

The equivalent remaining load facing a generating unit will depend on the unit's position in the dispatch order and the forced outage rates of all units previously dispatched. The equivalent remaining load duration curve is derived from the original load duration curve in a "step-by-step" procedure as each unit is dispatched. That is, the remaining load -- in megawatts -- is reduced by the capacity of each unit when that unit is dispatched, but is adjusted in each instance to account for the probability that the unit is unavailable (i.e., on forced outage).

Thermal Plant Representation. Thermal power plants can be divided into capacity "blocks" to approximate the actual variable levels of output and performance in real life. Each block can be associated with a particular "heat rate" which is the ratio of input to output energy usually expressed in terms of Btu/kWh, thereby capturing inherent efficiency changes at different levels of output. Slow-start plants, which must be kept running at some minimal level so they can respond to anticipated load changes, can be operated at the lower block levels. Unit commitment is an overall system target of capacity over and above the peak load that can necessitate that lower blocks of "committed" plants be run even when cheaper resources are available.

Hydroelectric Plants. Pondage hydro plants are aggregated into a single entity with specified weekly total capacity and energy. They are used in such a way that all of their energy is used up at the "top" of the load duration curve, i.e., in a peak-shaving manner. Computationally this is achieved using a method called "equivalent thermal dispatch" whereby, during the dispatch of thermal plants, before dispatching the next thermal block, a test is done to see whether there is enough "space" under the equivalent load duration curve after the block is dispatched for the storage hydro energy to "fit"; if not, then the hydro plant is dispatched beforehand, otherwise the thermal block dispatch proceeds. Pumped storage hydro electricity is calculated either through an optimization procedure or specified exogenously. The optimization compares the cost, including pumping losses, of using "excess" energy from previously dispatched plants to pump up the reservoir, to dispatching the next thermal block. If the pumped storage cost is cheaper and there is room under the equivalent remaining load duration curve, then pumped storage is dispatched and the pumping energy is credited to the appropriate thermal plants.

Input Assumptions

Price trajectories for various fuels were estimated by EGAT and other government agencies and discounted to real 1989 price levels [EGAT, 1989]. Actual 1986 operating and maintenance costs were aggregated by generation technology type and used in ELFIN [EGAT, 1988]. Hourly loads for all of fiscal year 1987 (October - September) were collected and from which 12 typical weeks were derived. Weeks were chosen on the basis of a match of average energy and load factor for the month, with the exception that the week containing the annual peak was substituted where it occurred. EGAT's unit commitment level was found to be, on average, 16% above the peak load, based on the operating records and predictions between October 1987 and September 1990. Three plants[6] totaling 2163 MW in 1989 were specified as must-run plants for local voltage support.

Plant performance data in the form of maintenance outage rates, forced outage rates, and heat rates were drawn from [EGAT, 1988]. Maintenance outages ranged from 4 to 8 weeks and typically followed a repeating three-year cycle (e.g., 4-4-6-4-4-6-4-4-6, etc.). Forced outages were based on experience with existing facilities and estimates for future plants. All forced outages in multiple-block plants were modeled to occur on the last thermal block. Average and incremental heat rates were calculated using EGAT's coefficients from a quadratic heat rate formula. Weekly hydro energy and capacity inputs were developed from EGAT's internal data on past performance and stream flows. All hydro capacity and energy are operated as dispatchable pondage hydro. For the purpose of producing the power development plan EGAT

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[6] Bang Pakong units 1-4 (thermal), Mae Moh units 1-7, and North Bangkok units 1-3.

uses the conservative assumption of dry hydrologic conditions. Hydrologic years are often delineated by "exceedence" levels, defined as hydroelectric generation in X% of the years exceeding that of the given year. Thus for its dry year assumption EGAT uses a 90% exceedence level. Both average and wet hydroelectric profiles were also developed for this study (50% and 10% exceedence levels, respectively). Pumped storage hydro units were modeled to optimize their performance in accordance with ELFIN algorithms, rather than replicating the generation depicted in EGAT [1988].

Base Case

Using the above inputs to ELFIN we calibrated the base case simulation to that of EGAT. In projecting the level of plant generation and fuel consumption to 2006, EGAT uses the production-cost module contained in WIGPLAN. Examination of hydro energy production projections with other data filings suggests that EGAT used average-year hydro data in this case, instead of the usual dry-year hydro data used in their capacity expansion planning. We adjusted ours to the same 50% exceedence hydroelectric generation. Table 4A shows the percentage differences in energy generation between ELFIN and WIGPLAN from plants grouped by fuel category. The two models are in general agreement with one another, to within 5% generally, with some exceptions[7]. The departures are partially explained by differing assumptions about the timing of plant commissionings, about energy purchases, and hydro generation. Data were not available to rectify these discrepancies, but in any case they were not considered large enough to prejudice subsequent analysis. Other indices used in performing calibrations between production-cost models, such as marginal and total costs also were unavailable.

The picture of energy generation, installed capacity, and cost structure predicted by the base case ELFIN simulation is shown in Table 4B. The most notable feature of the Thai base case is that, in terms of both energy and capacity, EGAT moves from a heavy reliance on oil and domestic gas in 1991 to one on domestic lignite and imported coal by 2006. Hydro capacity, though increasing in the absolute, grows more slowly than capacity overall and thus falls to 18% in 2006 (from 27% in 1991). As is typical with hydroelectric power, the energy generation contribution is much smaller in relation to capacity, from 11% in 1991 to only 6% in 2006. Purchased power from Laos and Malaysia contributes only marginally to the Thai system. As with generation, total costs nearly treble between 1991 and 2006, while marginal costs remain relatively flat. LOLPs range from .007 to .281 days/year, all far below the planning threshold of 1 day/year.

Wet and Dry Hydro Year Cases

Because hydro generated electricity displaces the most expensive alternate sources, and because Thailand has rather large installed hydro capability, we looked at the sensitivity of the simulations to the quantity of hydro dispatched. Specifically, we looked at dry and wet year conditions, or 90% and 10% exceedence levels, respectively. Table 4C tells the story. In the early years of the dry scenario, all of the deficit is met by oil and gas generation, whereas by the turn of the century lignite and coal begin to account for a large share, and by 2006 comprise nearly the total. Total costs increase about 30 million U.S.$ in each year, which is 4% in 1991 of the total, falling to 1% in 2006. Marginal costs increase between .2 and .4 mills/kWh, which amounts to 1% or 2% of base marginal costs. LOLP steadily increases .021 days/year in 1991 to .288 days/year in 2006.

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[7] Much larger discrepancies were found in comparisons of energy generation between individual fuels, the main problem appearing between the oil and gas plants. It is known that many of EGAT's boilers possess dual-fuel capability, and that, in predicting fuel consumption, EGAT performs "post-processing" to adjust their simulation results to match up with estimates of the availability of natural gas. Excess generation in the dual-fuel plants is then dedicated to imported oil.

The wet scenario is almost the mirror image of the dry, except that the magnitude of the hydro change is greater in the former. Even so, LOLPs do not improve commensurate with the change in hydro, illustrating the non-linear nature of the reliability indicator. Marginal costs decline about 3%. Note that the other sources in some years generate somewhat more or less GWhs than the change in hydro depending on changes in pumped storage generation with accompanying pumping losses. Recognizing the large uncertainties inherent in any exercise involved in projecting future outcomes, the level of hydro generation does not appear to influence the results beyond those error margins.

CONSERVATION SCENARIOS

The previous chapter described energy conservation opportunities in prototypical Thai offices, retail buildings, and hotels. In this section we will extrapolate, by means of a simple spreadsheet model, from these individual buildings to the commercial sector as a whole. With this model, different conservation scenarios in the commercial sector are explored. These scenarios are later entered into ELFIN for the purpose of simulating their impacts on the Thai power system (described below).

Commercial Sector Model

The model of commercial sector electricity use is built upon the patterns (or "shapes") of electricity demand from the prototypical buildings. Figure 4C shows the diurnal load shapes typical of Thai offices, hotels, and retail outlets. These load shapes were generated by taking hourly results from the DOE-2.1D building energy simulation program binned by hour-of-the-day and averaging them. Seasonal variation in the load shapes was found to be insignificant, as Figures 4D through 4F will attest. For this reason, a single load shape was adopted to represent each of the three building types[8]. The load shapes are expressed as twenty-four values in W / m^2 and combined with floor area estimates to yield total load patterns.

As no tabulation or forecast of commercial floor space has been undertaken in Thailand to date, estimates were made in the following manner. First, the electricity forecasts by business classification for the Large Business customer class were allocated to specific building types: wholesale and retail trade into retail buildings; banking and insurance, other market services, and non-market services into office buildings; hotels and restaurants and specific business into hotel buildings. These GWh trajectories by building type were converted into floor space trajectories by dividing them by the energy intensity (in kWh / m^2) from the simulated prototypes. The validity of this approach was tested by comparing the typical diurnal load shape for the Large Business class within MEA territory, where the vast majority of commercial buildings are located, and comparing the result to the model's calculated load shape using the floor space estimates and simulated building load shapes. This comparison is shown in Figure 4G. A remarkable match was found between them, although the simulated load shape showed more "sharp" discontinuities due to so few buildings representing an entire class. These discontinuities were smoothed using simple multiplicative factors applied hourly in every year of the projections to 2001 to account for more diversity of use in many buildings. The effect of the diversity factors is shown with a separate curve in Figure 4G.

Having represented electricity demand patterns by commercial building type into the future, we developed the capability to model changes to those patterns that would result with

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[8] Only the office building operated on a schedule that differed by day-of-the-week, but it was thought that the slight increase in accuracy that differentiating by day-type brought overall did not warrant the increased model complexity.

conservation and load management activities. The conserving cases (described below) were developed in the same manner that the individual building load shapes for the base case were derived. However, instead of simply multiplying by the respective floor areas, the conserving cases use only the floor area that has adopted the conservation technologies, in the form of penetration rates. Penetration follows an exponential profile over time and is meant to approximate the process of market acceptance or incipient program effectiveness. The model takes as input the target total penetration rate at the end of the time horizon and the annual rate of penetration in new buildings. The model calculates a year-by-year penetrated floor area stream for new, existing, and all buildings[9]. Figures 4H and 4I show the cumulative and yearly penetrated floor area, respectively, for an example penetration rate of 67%, which is comprised of annual new building penetration of 100% and average annual existing building penetration of 3%. The typical hourly profile of the conservation scenario is the product of the penetrated floor area and the individual building load shapes. Then, scenario MW savings are simply the difference in each hour between the base and conserving case commercial sector load. The savings in total generation requirement is determined by increasing the savings by 15% to credit the power system losses that the conserving case avoids [EGAT, 1989].

Four illustrative conservation cases were developed based upon parametric simulations of prototypes of Thai commercial buildings described earlier. Each case relates to either promising technologies, or specific policy approaches to promoting the technologies, or both. The cases are high-efficiency (HE), building energy standard (ST), load-shifting (LS), and non-electric cooling (NC). An example office, hotel, and retail building are represented, each having been found to provide significant energy savings over the typical situation and to be financially attractive to the building owner. This in no way is meant to imply that these are the only choices available for conserving energy, nor that they are necessarily the best choices. They are presented here simply to illustrate a range of possibilities, and their likely impacts on the power system.

High-Efficiency. This case utilizes a mix specific to each building type of the most efficient and cost-effective commercially available conservation technologies. These include efficient chillers and fans, variable-air-volume air-conditioning systems, efficient luminaires, ballasts, and bulbs, and space temperature control that meets Thai office worker comfort demands.

Building Energy Standard. This case meets the requirements of the proposed energy standard for new commercial buildings. It includes threshold levels of lighting power density, chiller efficiency, and heat gain from the building envelope. Many paths to compliance exist and this case only illustrates one for each building type. Only the minimum modification to meet the standard was modeled.

Load-shifting (TES). This case utilizes chilled water to augment the chiller during periods when the building experiences its peak building and cooling loads. This allows the chiller to be sized smaller than usual, but forces it to operate most of the time, either cooling the building directly or chilling water for later use. This is known as "partial" storage to distinguish it from "full" storage which schedules the chiller to be off completely during the peak period. In each case the storage and chiller were sized to optimize the savings from the *building owner's* point of view.

Non-Electric Cooling. This case depicts the use of gas-engine chillers to replace the more conventional electrically-powered vapor-compression chillers. This, in effect, eliminates the cooling contribution to electricity demand, which is typically in the range of 40-60% of the total.

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[9] Note that the penetration rates are equal among building types.

Figures 4J through 4L are load shape plots of the conservation cases. They show the typical daily patterns for offices, hotels, and retail buildings, respectively. The high-efficiency and building energy standard cases have little impact on the shape of loads; they mainly affect the the magnitude. On the other hand, the load-shifting case reduces the peak loads by shifting them to off-peak, but in the process increases overall energy use. The non-electric cooling case both lowers and alters load shape. In addition, the cases have different relative effects among building types. The high-efficiency case, while reducing loads the most in all cases, reduces peak load by 55% in retail outlets and 50% in hotels, but only by 40% in offices. In terms of peak intensity, the high-efficiency office reduces to 50 W / m^2, the retail to 42 W / m^2, and the hotel to 29 W / m^2. The building energy standard is the next most effective case, although non-electric cooling is quite comparable in offices. In hotels the non-electric cooling case has only slightly higher electric loads than the building energy standard, but in retail buildings the difference is substantially greater, reflecting the greater proportion of non-cooling demand in retail establishments. Thermal storage in the load-shifting case has the greatest impact on offices, shaving the peak by over 20% and somewhat less over the occupied period, but substantially increasing the off-peak demand. Retail load-shifting achieves a reduction of 12% consistently during occupied hours (and again increases loads greatly off-peak), whereas in hotels the load reductions, which take place within a three-hour period in the late afternoon/evening, and increases at all other times, are very modest.

Penetration rates. The conservation cases are combined with different penetration rates to define conservation *scenarios.* While the cases relate to individual buildings, the scenarios encompass the commercial sector as a whole. The set of scenarios for each conservation case is tailored to the technology or to policies applicable in the case. Each case has a 100% penetration case which, while admittedly optimistic, is interesting from the standpoint of assessing technical potential. Other scenarios base their penetrations on U.S. utility experience with conservation programs (Nadel, 1990). In the building energy standard case, the scenarios show combinations of mandatory and voluntary standards for either new or existing buildings or both. Table 4D shows the twelve scenarios of this study, their annual penetration of new and existing buildings, the ultimate penetration at the end of the scenario time horizon, and the proportions of the total between new and existing buildings. As an example, Figure 4M displays the yearly progression of hourly load savings for the scenario of mandatory new building energy standards with incentives to owners of existing buildings to promote retrofits that meet the standard (ST-67%). All scenarios have an eleven-year timeline, beginning in 1991 and "ending" in 2001. The load impacts are assumed to persist beyond 2001 but cease to grow, as in the case of a terminated program or incentive. For the remainder of this paper, scenarios will be identified by case and ultimate penetration.

SUPPLY IMPACTS OF CONSERVATION SCENARIOS

The conservation scenarios described above cause load changes that affect the operation of the power system. In the short run, or when load impacts are modest, conservation simply lowers the costs of generation. Over the longer term, however, larger load impacts decrease the need for new capacity, arguing for a structural adjustment in the composition of the supply system. Conservation scenarios thus create the opportunity for deferring or even cancelling planned power plants. At the same time, revenues collected from electricity sales are lowered. Thus, conservation can result in either a net cost or a net benefit to the utility, depending on the electricity rates and value of avoided power. In this section we discuss methods for evaluating the value of conservation to an electric utility and then present the implications, operational and financial, of implementing the conservation scenarios.

Method for Valuation of Conservation

When load perturbations are relatively large, the true value of conservation is the change in the planned supply that the load reductions enable. But this "value" is expressed in an action, i.e., structural change, and not in monetary units. To quantify this value, we follow the methodology found in Kahn [1989; 1988] and Eto [1988]. The first step is to run a production simulation, referred to as simulation one (S1), of the base case supply plan with the original load forecast (already described). The next step is to simulate the implementation of the conservation scenario (that is, reduce loads) with the base supply plan. This latter simulation, S2, will yield lower costs. Now deferrable plants are identified. The criteria used was to identify plants whose physical works were not yet underway at the outset of the conservation program, using 1991 as the year of program commencement. Other considerations include the size and timing of deferrable units, and in some sense, congruity between the duty cycle of the plant(s) targeted for deferral and the nature of the load impacts. For instance, for a load-shifting conservation scenario, one would want to target plants used for peaking or load-following.

It is necessary for the conservation scenarios to have a chance to build up sufficiently large load impacts before plant commissioning dates can be delayed. Fortuitously perhaps, the long construction lead times typical of power generation plants can result in the commissioning dates of the earliest deferrable plants roughly coinciding with the occurrence of minimum load impacts. Also, the principle of present value mathematics dictates that a greater cost impact is obtained from deferring plants scheduled to come on line earlier in the plan than later, all other things being equal. When an expansion plan contains as many potentially deferrable plants as Thailand's does, and in spite of the foregoing guiding considerations, multiple solutions are still possible. Exogenous considerations may play a role in narrowing the choices of deferrable plants, such as siting, fuel diversity, or other issues of concern to utility planners. Only thermal plants in the plan were considered for deferral here, but in principal hydro plants could also be deferred. No a priori preference was given for any particular thermal plant technology or resource in selecting deferrable units.

The next simulation, S3, again incorporates the conservation scenario, but this time alters the supply plan by deferring plants. This will result in higher costs than S2 because more expensive resources are used in the absence of the deferred plant(s). The net present value (NPV) of the stream of production costs from this simulation is then compared to that of the base case. Using this method, the goal is to find the cost-neutral modified supply plan defined in the following manner.

$$\text{NPV (S3)} = \text{NPV (S1)} \tag{4B}$$

Solving Equation 4B requires an iterative technique, deferring different plants and combinations of plants until equivalence is reached.

With the optimal deferral thus identified, one final simulation (S4) estimates the monetary value of the conservation scenario. This is based on the modified supply plan, but now assuming the original load forecast (i.e. without conservation). The difference in the discounted sum of production costs over the lifetime of the deferred plants between the base case and the modified supply plan using the original loads approximates the monetary value of deferral due to conservation.

$$\text{Deferral Value} = \text{NPV (S4)} - \text{NPV (S1)} \tag{4C}$$

All simulations extend to the end of the utility planning horizon which is 2006. However the deferred plants could be expected to operate another 25 or years or so beyond the final simulation year. The horizon is extended by using an end-effects procedure which amounts to duplicating the final-year simulation to 2030.

A problem arises with this approach when a system's reliability changes faster than production costs. The costs of changes in system reliability should be internalized. If, for example, reliability is allowed to decrease, this can lead to extremely large deferrals that are disproportionate to the load impacts. Moreover, this situation calls into question the reasonableness of the results in S3 and S4 because of large LOLPs and unserved energy and because models do not give reliable results at the extremes. A further re-optimization of the supply plan is called for to avoid such cases. We therefore impose another condition on the optimal deferral, namely that the conservation scenario with modified supply plan (i.e., S3) must maintain equivalent system reliability (as measured by LOLP) as the base case (S1).

$$\mathrm{LOLP(S3)} = \mathrm{LOLP(S1)} \tag{4D}$$

We do this with the introduction of gas turbines, which traditionally serve the reliability needs of power systems. Gas turbines are used in this way because of their relatively low fixed costs and quick-start capability, and since they are used so infrequently, their characteristic high variable costs do not add significantly to system production costs.

Gas turbines (GT) are incorporated into the simulations of S3 and S4 and their investment costs are inserted into the stream of production costs of S3 and S4 in the year(s) the GT units are introduced. Gas turbine investment costs were taken as the average capital cost of proposed GT plants in the utility capacity expansion plan (i.e., $ U.S. 540 per kW) converted to a present worth of revenue requirements of capitalization at commissioning date. The above conversion is done to account for the present worth of return, depreciation, taxes, insurance, administrative and general expenses incurred over the lifetime of the investment. For the U.S. utility industry, the nominal plant capital cost is typically multiplied by a factor in the range of 1.6 to 1.7 to reflect the present worth, at the commissioning date, of all future revenue requirements [Leung 1978; Lyons 1979]. However, for Thailand's publically-owned utility, assuming that there is no tax on equity returns (which is a large component of the total factor), and without knowledge of their other financial parameters, we assumed a factor of 1.2.

$$\mathrm{GT\ cost}_{t=c} = \frac{\$540\mathrm{(U.S.)}}{\mathrm{kW}} \times 1.2 \tag{4E}$$

Note that Equation 4E calculates the present worth *at the time of plant commissioning* (i.e., at time t = c). Thus, consistent with the treatment of the production cost streams, the GT costs are discounted to the base year of the analysis. Equations 4B and 4C are modified in the following manner.

$$\mathrm{NPV\ (S3^*)} = \mathrm{NPV\ (S3)} + \mathrm{NPV\ (GT\ cost)} \tag{4F}$$

$$\mathrm{NPV\ (S3^*)} = \mathrm{NPV\ (S1)} \tag{4G}$$

This adjustment places S1 and S3* on an equal reliability basis. Including gas turbine investment costs in Equation 4F serves to reduce the magnitude of unadjusted plant deferrals necessary to get the stream of costs in S1 and S3 to agree. The resultant net deferrals become closer in scale to the load impacts (on a megawatt basis) of the conservation scenarios that permit their consideration.

Calculating the value of deferral while satisfying Equation 4D proceeds as above by incorporating the discounted value of added gas turbines into the stream production costs of simulation S4.

$$\text{NPV (S4*)} = \text{NPV (S4)} + \text{NPV (GT cost)} \tag{4H}$$

$$\text{Deferral Value} = \text{NPV (S4*)} - \text{NPV (S1)} \tag{4I}$$

Ideally, one would declare that the system reliability in simulation S4* (where the supply plan is modified, but the load forecast is fixed) also be identical to that of the base case simulation S1. This condition is, however, difficult to satisfy in practice without further changing the supply mix (through the addition of even more GTs) from that of S3*. Unless load impacts (and hence deferrals) are small, simultaneously satisfying this condition and Equation 4D with the same supply plan is virtually impossible. Another problem is that the relationship between S3* and S4* would lose meaning should the supply mix be different between them. Balancing these concerns, we impose the more modest condition that the reliability of S4* and S1 remain *roughly* similar.

$$\text{LOLP (S4*)} \approx \text{LOLP (S1)} \tag{4J}$$

Equation 4J is evaluated by ensuring that LOLPs are comparable in *most* years of the simulation period, and that, in any case, the utility reliability criteria are not significantly violated in the years in which the LOLPs diverge. In the present analysis, Equation 4J was basically fulfilled[10] without further adjustments to the supply plan between simulations S3* and S4*.

The imposition of a reliability equivalence condition is an extension of the methodology developed by Kahn [1988, 1989]. This re-optimization of the supply mix involves a greatly increased simulation burden because one must search for equivalence both in cost and reliability. However, it does represent a more valid comparison between perturbed and base supply plans because a utility can always reduce cost by allowing system reliability to deteriorate. To clarify the nomenclature of simulations complicated by the reliability constraint, we direct the reader to Table 4E.

Results

Short-run values of the conservation scenarios are presented in Table 4F. They are the production cost savings that accrue to the load changes from conservation, without any change in the supply plan. The savings are summed over the planning horizon to 2030 and discounted to the year of scenario initiation (1991). For this study, a seven percent *real* discount rate was used in all present value calculations, derived from the Thai utility's nominal discount rate of 12% adjusted for inflation [EGAT 1989]. Substantial savings come from all scenarios of the high-efficiency, building energy standard, and non-electric cooling cases. At one end of the range, the technical potential high-efficiency scenario (HE-100%) saves $ 1414 million over the twelve-year horizon, while at the other end of the spectrum the voluntary building energy standard scenario (ST-3%) saves $ 19 million. Load-shifting in all penetration scenarios actually results in increased production costs. This is because loads are shifted away from customer peaks but not necessarily away from EGAT's peak, and because energy requirements are larger overall from efficiency losses in the thermal storage system. Savings in production cost in the other scenarios are accompanied by improvements in the reliability (shown in the last two columns of Table 4F). These LOLPs are much lower than those from the base case and well in excess of EGAT's reliability criteria. The greater benefit of conservation programs is the ability

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[10] In the latter years of several scenarios' S4 simulations, the LOLP were higher than their S1 counterparts, but the differences were judged sufficiently small to ignore. In only one year of one scenario's S4 simulation the LOLP reached 1.3, exceeding the Thai utility's criteria of less than one day per year.

to slow utility investment in new capacity, and for this reason we turn next to analyzing the scenarios from that perspective.

Table 4G shows, for each conservation scenario, the amount of capacity deferred, the capacity of gas turbines added for reliability, and the value of the deferral as calculated in Equation 4G. Scenario peak and energy impacts in 2001 are presented in the same table for comparison. Note that the peak impact shown in the table is that which is coincident with the *system* peak, but that each scenario reduces the *class* peak by a far greater amount, up to 70% in some scenarios. The high-efficiency 100% penetration scenario has a net present value of $ 1.6 billion over the would-be lifetime of the deferred plants. This scenario captures the greatest value by far from deferrals and represents the ultimate potential value of electricity conservation in commercial buildings for the utility. The value of the other scenarios follows roughly in line with their respective load impacts. Deferral value is not strictly proportional to penetration rate among cases (e.g. high-efficiency, non-electric cooling, etc.) as one might expect, in part because the 100% penetration scenarios assume that the conservation has fully penetrated all available floor space in each year. Because there is so much existing floor space at the commencement of the conservation scenarios, the load impacts in the early years are much higher in the scenarios depicting technical potential than in the others which predict a more gradual progression to their ultimate penetration level. Early load impacts are given higher value because of discounting. It is also likely that the mix of generation resources used in each scenario differs and that this partially contributes to a lack of direct correlation of value between scenarios. No plant deferrals were possible under any load-shifting scenarios because those scenarios increased production costs.

A close examination of Table 4G reveals that the peak impact plus the capacity of added gas turbines is less than the capacity of deferred plants, yet the scenarios maintain reliability equivalence with the base case. This is because the scenarios shift more loads during peak periods than during others, thus "flattening" the overall load shape and this has the effect of reducing LOLP for a given reserve margin. The result is a reduction in the excess capacity needed to maintain a reliable system. This reliability "bonus" adds capacity value to the load impacts and can be a substantial portion of the overall impact of conservation scenarios on power systems.

The inverse holds true when adding power plants to a system: the reliability effect serves to reduce the value of installed capacity. In other words, some of that installed capacity serves incremental reserve margin requirements. This concept, also known as the "effective capability" of power plants, draws a relationship between unit size and forced outage rate, and system reliability [Garver 1966; Lyons 1979]. The same relationship holds for deferred capacity following demand shifts. The size of the saved incremental reserve requirements will be particular to a given system and the power plants deferred. For a given conservation scenario, the sizes and forced outage rates of plants both remaining in the system and deferred by conservation will determine the magnitude of the reliability effect. The reliability benefit comes about through two phenomena: spreading the risk from flattening the load, and avoiding installation of capacity that is inherently unreliable (from forced outage). In general, the larger the deferred units and their forced outage rates, the larger the reliability bonus will be.

From the conservation scenarios in Thai commercial buildings, every one percent reduction in the reserve margin required by 2006, yields an additional 200 MW of unneeded capacity in Thailand. Table 4H compares the average reserve margin from the base case with those from the conservation scenarios. Reserve margins from the conservation scenarios were drawn from simulations using both modified supply plan and load trajectory, i.e. simulation S3*.

Re-optimizing the supply plan is necessary because conservation lowers both the required reserve margin and energy requirements. Table 4I shows how these components make up the net deferral. For each scenario, the amount of deferred capacity related to energy and that related to reliability gains is shown, along with the net deferrals for comparison. The energy related deferral is based on an equivalent baseload capacity using the average annual operating hours of the deferred plants (i.e. capacity factor of 84%) and the annual electricity impact from Table 4G. The values for the reliability related deferral are based on the data in Table 4H and the expected capacity of 23,000 MW of the base case power system in the year 2006. The significance of the reliability bonus is readily apparent. In most cases reliability gains account for more than half of the net deferrals of the conservation scenarios. Where the net deferrals differ from the sum of the deferral components, the discrepancy can be found in the averaging process over the simulation period for reserve margin and deferred plant capacity factors.

An explanation for why the reliability component of net deferred capacity is so large can be found in Table 4J where capacity factors of coal plants in 2006 for the conservation scenarios are compared prior to, and following plant deferrals (i.e., using simulations S2 and S3*). Capacity factors of typical baseload plants are in the range of 70% to 80%. The conservation scenarios depress the already low baseload capacity factor in the base case of 63.3% to as low as 56.4%. Baseload plants are, in effect, being used to support the reliability needs imposed on the system by other baseload plants. Using large baseload plants for reliability purposes pushes system reserve requirements even higher. By deferring some of those baseload plants, and meeting reliability demands with peaking units, incremental reserve margin requirements of the deferred plants are also saved. Furthermore, as Table 4J shows, the re-optimized system following plant deferrals utilizes baseload plants at more customary levels.

Other studies of the potential for deferring capacity from conservation have shown much more modest results [Eto 1988; Kahn 1989]. This is in part because the conservation scenarios investigated in those studies had smaller load impacts, but also perhaps because the systems in which the scenarios were applied were growing at a far slower rate. Electric utilities with relatively slow demand growth have few plants to defer in their supply plans. This was typical of utilities in industrial countries of the last decade. Developing countries, on the other hand, are generally experiencing high electricity demand growth. A proposition we offer is that the potential for capacity deferral due to conservation is greater in developing nations where power systems have much capacity to defer.

Conservation generally reduces the revenues collected by the utility. Whether revenue losses are offset by operating cost savings depends on the tariffs facing customers and the nature of the load changes. While acknowledging the importance of this issue for the utility, without information on how future tariffs might be set in Thailand and, in particular, how system fixed and variable costs are allocated among customer classes, especially under changed load regimes represented in the conservation scenarios, no prediction of the financial impacts of the conservation scenarios was undertaken.

Also absent from a full depiction of the financial picture of utility impacts from conservation is some indicator of the scarcity of capital. In the valuation of the scenarios, one would want to count the opportunity cost of using capital to build power plants in lieu of other productive investments. Table 4K shows a crude comparison of the capital requirements of the conservation scenarios[11] versus the cost of capital they displace (in nominal terms), where the cost of deferred capital is net of the investment in gas turbines for reliability. The incremental capital cost of the scenarios is based on installation in new buildings and so underestimates the cost in a retrofit situation. Yet, even if the scenario capital requirements were doubled (which is unlikely even when strictly accounting for the cost premium of retrofits), they are less than half

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[11] Investment costs for the building energy standards case were not calculated.

those of the deferred power plants. Additionally, the deferred capital cost ignores the savings from avoided transmission investment. From a societal point of view, therefore, the conservation scenarios are beneficial in that they free up scarce capital that can be put towards other development needs.

CONCLUSIONS

Drawing on the building energy simulation results, impacts on the Thai electric utility were evaluated under various conservation scenarios. The scenarios were represented in the large building commercial sector by four technology packages: high-efficiency, building energy standard, non-electric cooling, and thermal energy storage. A model was developed that allowed sectoral energy use projections using inputs of energy intensities and hourly demand profiles by building type, and scenario penetration rates. Using the ELFIN utility planning model, simulation of the power system to the year 2006 under these scenarios revealed substantial cost and reliability benefits of conservation to the Thai utility. However, the primary value of conservation scenarios is in the opportunity to defer or cancel plants planned for future inclusion in the system. The benefits are twofold: a direct reduction in capacity needs commensurate with the load impacts of the scenario, plus a reduction in the reserve margin required to maintain system reliability. For example, the high-efficiency, 50% penetration scenario permitted a net deferral of 700 MW, while the direct peak load impact of the scenario was only 300 MW. The estimated monetary value of capacity deferrals, likewise, was considerable; for the same scenario it exceeded $ U.S. 500 million. Comparison of the capital requirements of the conservation scenarios versus the deferrable plant capacity, showed that conservation was one quarter as capital intensive.

Table 4A.
Base Case ELFIN Calibration to WIGPLAN Simulations (selected years)
(percentage differences in energy generation)

	1991	1996	2001	2006
Oil & Gas	-4.6%	-7.1%	-7.1%	-2.6%
Lignite & Coal	3.3%	19.9%	9.7%	1.8%
Purchased Power	-7.6%	-3.0%	-3.0%	-3.0%
Hydro	27.2%	-4.5%	-6.6%	-4.8%

Table 4B.
Base Case ELFIN Simulation Results of EGAT System in Selected Years

	1991		1996		2001		2006	
ENERGY (GWh):								
Oil & Gas	29352	(63%)	43428	(61%)	44911	(46%)	37393	(29%)
Lignite & Coal	11003	(24%)	21834	(31%)	44931	(46%)	83167	(65%)
Purchased Power	684	(2%)	684	(1%)	684	(1%)	684	(1%)
Hydro	5273	(11%)	5698	(8%)	6866	(7%)	7238	(6%)
TOTAL	46312		71644		97392		128482	
CAPACITY (MW):								
Oil & Gas	5401	(57%)	8214	(58%)	8058	(43%)	5685	(25%)
Lignite & Coal	1459	(15%)	2925	(21%)	6575	(35%)	13200	(57%)
Purchased Power	98	(1%)	98	(1%)	98	(1%)	98	(0%)
Hydro	2514	(27%)	2933	(21%)	4000	(21%)	4116	(18%)
TOTAL	9472		14170		18731		23099	
Total Cost (M$)	941		1523		2016		2680	
Marginal Cost (mills/kWh)	19.0		19.2		19.1		21.6	
LOLP	.013		.007		.015		.281	

Table 4C.
Dry and Wet Years vs. Average Hydro Year:
Changes in Generation, Cost, and Reliability

	Units	1991	1996	2001	2006
DRY HYDRO:					
Oil & Gas	Δ GWh	1424	1435	1221	15
Lignite & Coal	Δ GWh	-1	0	439	1730
Hydro	Δ GWh	-1423	-1422	-1628	-1681
Total Cost	Δ M$	34	23	26	31
Marginal Cost	Δ mills/kWh	.2	.4	.3	0
LOLP	Δ days/year	.021	.038	.040	.288
WET HYDRO:					
Oil & Gas	Δ GWh	-2113	-2193	-1771	-175
Lignite & Coal	Δ GWh	1	-1	-463	-2187
Hydro	Δ GWh	2113	2192	2232	2345
Total Cost	Δ M$	-34	-32	-34	-38
Marginal Cost	Δ mills/kWh	-.6	-.5	-.3	-.5
LOLP	Δ days/year	0	-.003	-.004	-.039

Table 4D.
Penetration Rates in Thai Commercial Sector Conservation Scenarios

Scenarios	Annual New Buildings (%/yr.)	Annual Existing Buildings (avg. %/yr.)	Eleven-Year Final Total (%)	Proportion in New Buildings (%)	Proportion in Existing Buildings (%)	Notes
High-Efficiency	100%	n/a	100%	59%	41%	Technical Potential
	50%	4%	50%	58%	42%	Best U.S. utility programs†
	10%	1%	10%	58%	42%	Lighting and HVAC utility rebate programs†
Building Energy Standard	100%	n/a	100%	59%	41%	Mandatory both new and existing buildings
	100%	0%	54%	100%	0%	Mandatory new buildings only
	100%	3%	67%	80%	20%	Mandatory new, incentives existing buildings
	5%	0%	3%	100%	0%	Voluntary
Load-Shifting	100%	n/a	100%	59%	41%	Technical Potential
	20%	5%	40%	30%	70%	Best U.S. utility programs†
	20%	1%	20%	58%	42%	
Non-Electric Cooling	100%	n/a	100%	59%	41%	Technical Potential
	20%	1%	20%	58%	42%	Best U.S. utility programs†

† Based on U.S. utility program experience surveyed by Nadel [1990].

Table 4E.
Nomenclature Used to Describe Production Cost Simulations

Simulation	Base Case Loads	Conservation Scenario Loads	Base Case Supply Plan	Supply Plan w/ Capacity Deferrals	Supply Plan w/ GT Additions
S1	X		X		
S2		X	X		
S3		X		X	
S3*		X		X	X
S4	X			X	
S4*	X			X	X

Table 4F.
Production Cost Savings of Conservation Scenarios in Thailand's Commercial Sector

Scenario	Production Cost Savings * (M$)	LOLP in 2006 (days/yr)	Improvement in LOLP over Base
Base Case	-	.281	-
High-Efficiency 100%	1414	.038	86%
High-Efficiency 50%	524	.114	59%
High-Efficiency 10%	94	.235	16%
Building Energy Standard 100%	976	.083	70%
Building Energy Standard 54%	376	.144	49%
Building Energy Standard 67%	476	.122	57%
Building Energy Standard 3%	19	.272	3%
Non-Electric Cooling 100%	756	.115	59%
Non-Electric Cooling 20%	104	.236	16%
Load-Shifting 100%	-149	.458	-63%
Load-Shifting 40%	-45	.342	-22%
Load-Shifting 20%	-25	.310	-10%

* Savings are the 1991 net present value of savings between 1991 and 2030.

Table 4G.
Power Plant Deferrals and the Value of Conservation Scenarios in Thailand's Commercial Sector

Scenarios	Peak Impact by 2001 (MW)	Energy Impact by 2001 (GWh/yr)	Plants Cancelled or Deferred (MW)	Gas Turbines Added for Reliability (MW)	Value of Conservation (M$)	Changes to Power Plan
High-Efficiency 100%	625	5422	3150	1000	1630	Cancel Lampang Units 1-7, Saba Yoi Units 1-2; Add gt 500 MW each in 1998 and 2001
High-Efficiency 50%	312	2711	1200	500	531	Cancel Lampang Units 1-4; Add gt 500 MW in 1995
High-Efficiency 10%	62	542	300	100	103	Cancel Lampang Unit 4; Add 100 MW in 1997
Building Energy Standard 100%	415	3673	2100	800	949	Cancel Lampang Units 1-6; Add gt 200 MW each in 1996, 1998, 2000, and 2002
Building Energy Standard 54%	224	1983	900	400	358	Cancel Lampang Units 2-4; Add gt 200 MW each in 1997 and 2000
Building Energy Standard 67%	278	2461	1200	500	502	Cancel Lampang Units 1-4; Add gt 100 MW in 1995, 300 in 1996, 100 in 2004
Building Energy Standard 3%	12	110	300	35	20	Defer Saba Yoi Unit 1, Four Years; Add gt 35 MW in 2000
Non-Electric Cooling 100%	337	2977	1950	900	848	Cancel Lampang Units 3-7; Add gt 900 MW in 1996
Non-Electric Cooling 20%	67	595	300	135	114	Cancel Lampang Unit 4; Add gt 100 MW in 1997, 35 in 2001
Load-Shifting 100%	-275	-670	n/a	n/a	n/a	n/a
Load-Shifting 40%	-110	-268	n/a	n/a	n/a	n/a
Load-Shifting 20%	-55	-134	n/a	n/a	n/a	n/a

Table 4H.
Required System Reserve Margin from Conservation Scenarios in Thailand's Commercial Sector †

Scenario	Reserve Margin	LOLP in 2006 (days/year)
Base	19.1%	.281
High-Efficiency 100%	13.4%	.290
High-Efficiency 50%	17.4%	.298
High-Efficiency 10%	18.2%	.354
Building Energy Standard 100%	15.4%	.243
Building Energy Standard 54%	17.7%	.322
Building Energy Standard 67%	16.6%	.319
Building Energy Standard 3%	18.3%	.253
Non-Electric Cooling 100%	17.9%	.125
Non-Electric Cooling 20%	18.4%	.331

† Based on simulations using both adjusted supply plan and load trajectory, i.e., simulations S3.

Table 4I.
Components of Deferrals from Conservation Scenarios in Thailand's Commercial Sector

Scenarios	Plants Cancelled or Deferred (MW)	Gas Turbines Added for Reliability (MW)	Net Deferral (MW)	Energy-Related Deferral* (MW)	Reliability-Related Deferral† (MW)	Component Sum (MW)
High-Efficiency 100%	3150	1000	2150	740	1140	1880
High-Efficiency 50%	1200	500	700	370	340	710
High-Efficiency 10%	300	100	200	70	180	250
Building Energy Standard 100%	2100	800	1300	500	740	1240
Building Energy Standard 54%	900	400	500	270	280	550
Building Energy Standard 67%	1200	500	700	330	500	830
Building Energy Standard 3%	300	35	265	10	160	170
Non-Electric Cooling 100%	1950	900	1050	400	240	640
Non-Electric Cooling 20%	300	135	165	80	140	220

* Using baseload equivalent capacity (i.e., 84% capacity factor) of annual energy savings.

† Using the reduction in required reserve margin for constant LOLP.

Table 4J.
Baseload* Capacity Factors from Conservation Scenarios in Thailand's Commercial Sector

Scenario	Capacity Factor Pre-Deferral (%)	Capacity Factor Post-Deferral (%)
Base Case	63.3%	-
High-Efficiency 100%	56.4%	84.6%
High-Efficiency 50%	59.6%	70.8%
High-Efficiency 10%	62.6%	65.3%
Building Energy Standard 100%	58.3%	78.3%
Building Energy Standard 54%	60.6%	68.9%
Building Energy Standard 67%	60.0%	71.1%
Building Energy Standard 3%	63.1%	63.3%
Non-Electric Cooling 100%	59.3%	77.7%
Non-Electric Cooling 20%	62.5%	65.3%
Load-Shifting 100%	64.0%	-
Load-Shifting 40%	63.6%	-
Load-Shifting 20%	63.4%	-

* Capacity factors are the annual average for coal plants in year 2006.

Table 4K.
Reduction in Capital Requirements from Conservation Scenarios in Thailand's Commercial Sector

Scenario	Incremental Conservation Capital Cost (M$)	Deferred Power Plant Capital Cost (M$)
High-Efficiency 100%	748	3934
High-Efficiency 50%	373	1253
High-Efficiency 10%	75	309
Load-Shifting 100%	108	n/a
Load-Shifting 40%	44	n/a
Load-Shifting 20%	22	n/a
Non-Electric Cooling 100%	296	2119
Non-Electric Cooling 20%	59	290

Figure 4A.
Hourly Loads for EGAT System (1987)

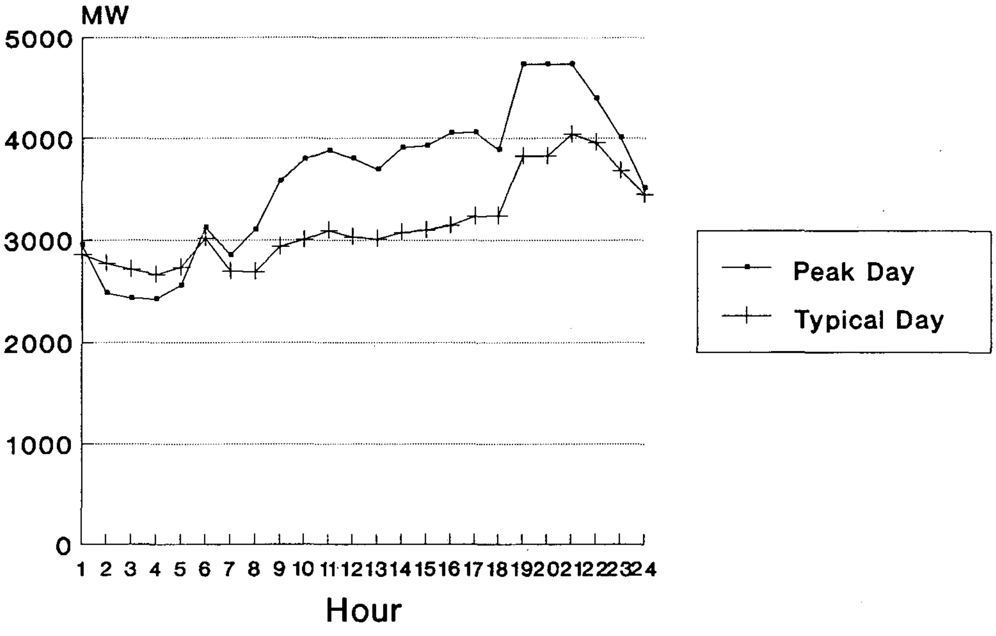


Figure 4B.
MEA Load Shape by Sector (1988)

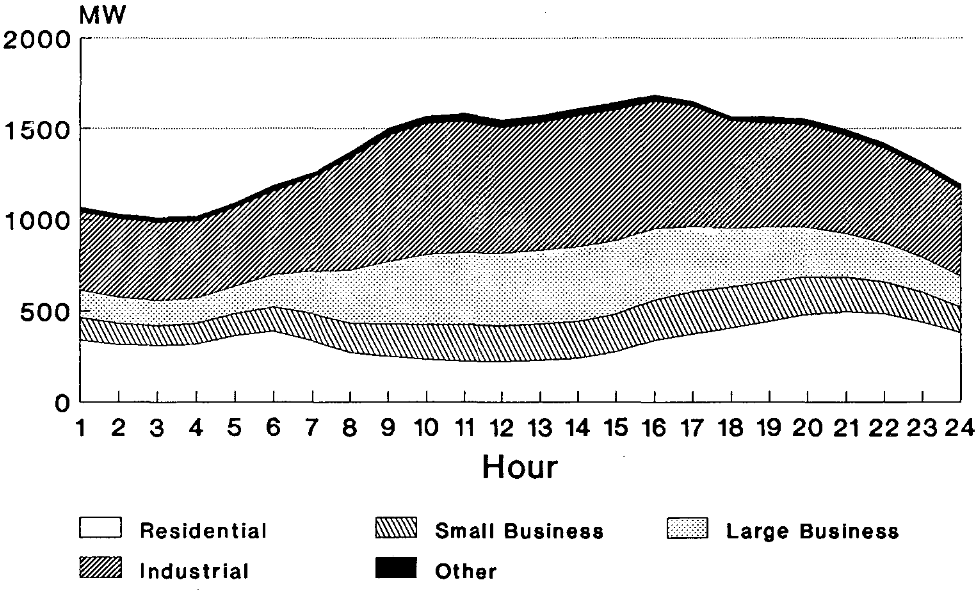


Figure 4C.
Thai Commercial Typical Load Shapes

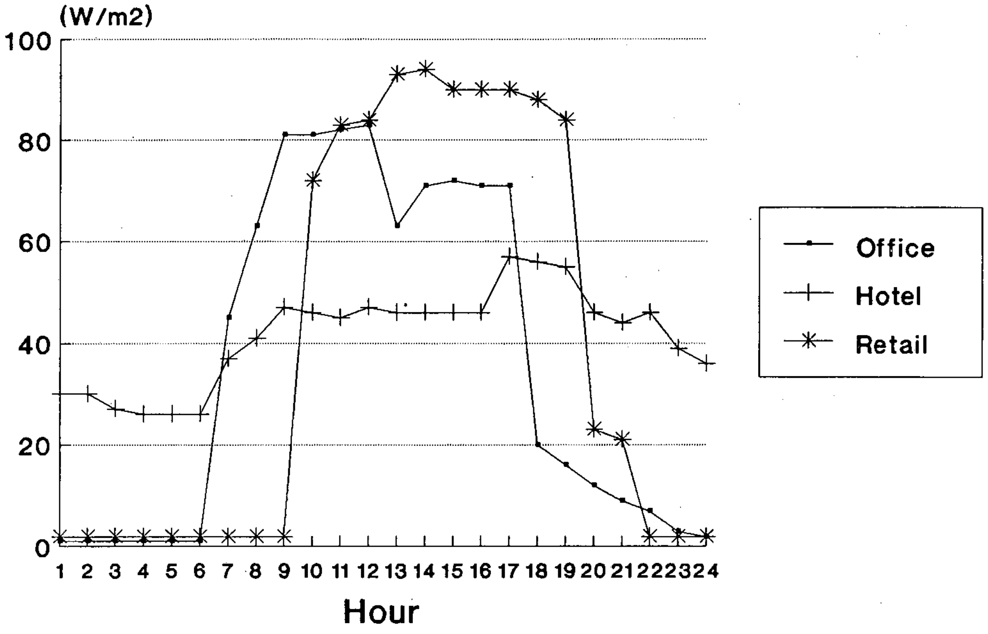


Figure 4D.
Thai Office Daily Load Shapes by Month

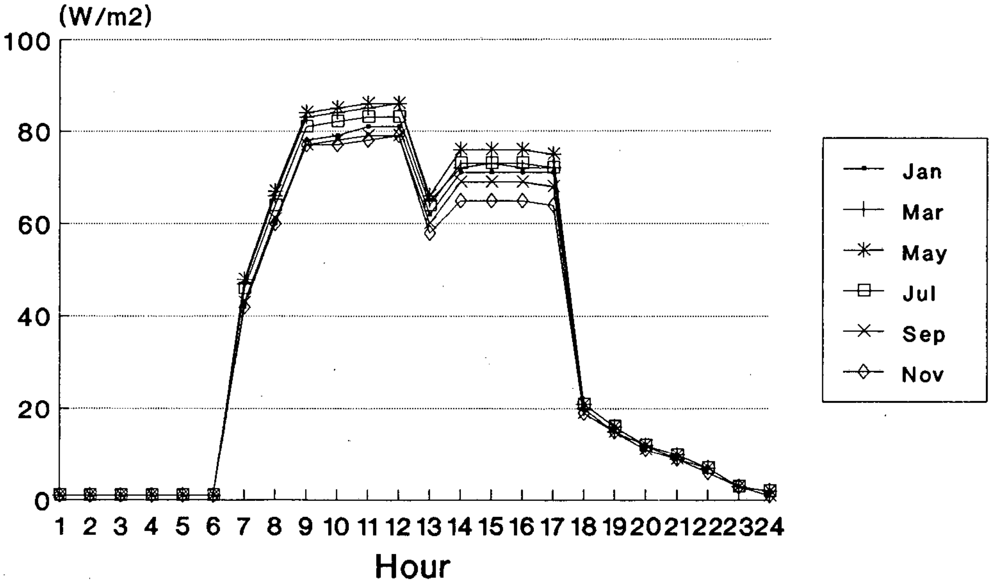


Figure 4E.
Thai Hotel Daily Load Shapes by Month

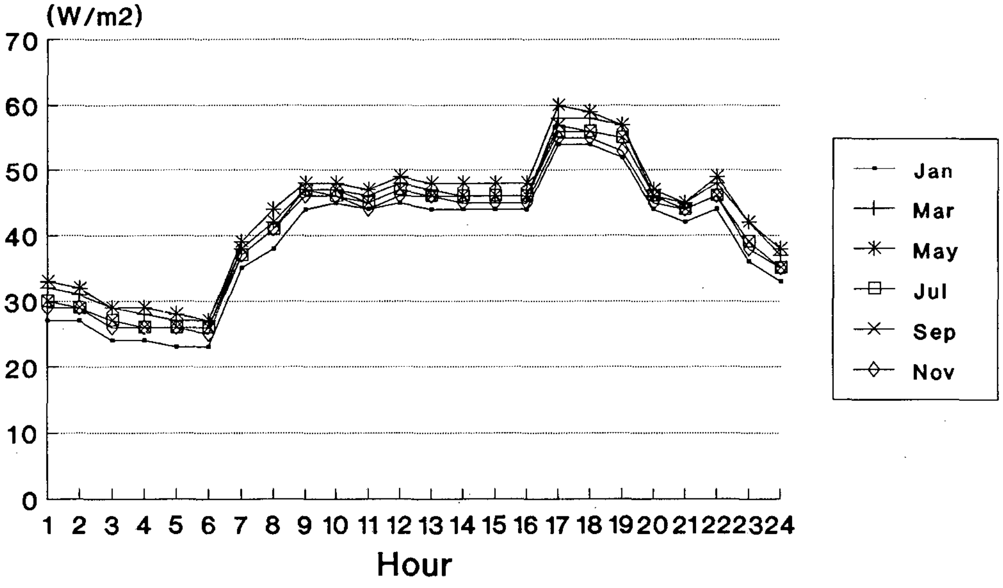


Figure 4F.
Thai Retail Daily Load Shapes by Month

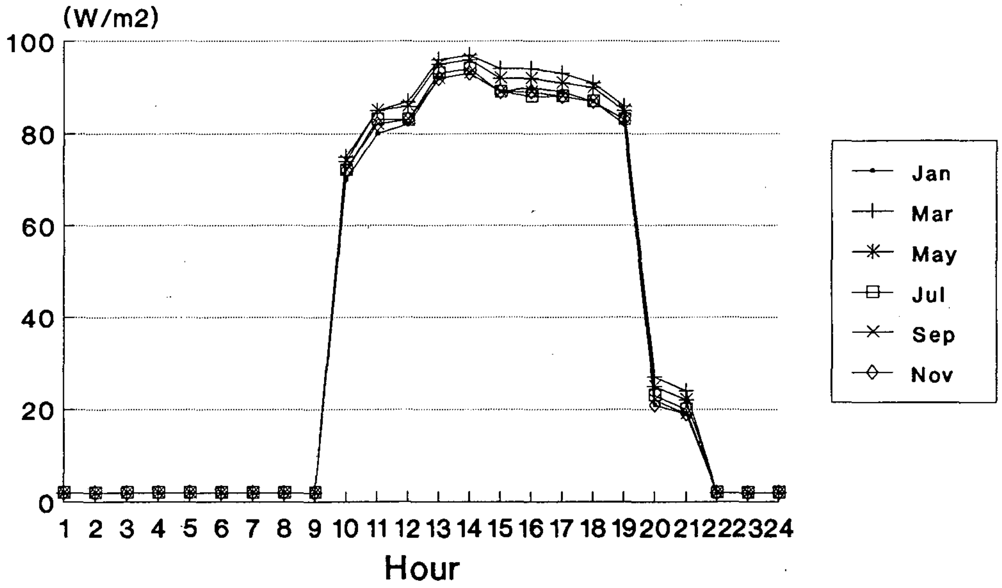


Figure 4G.
Comparison of Measured and Simulated MEA Commercial Sector Daily Loads

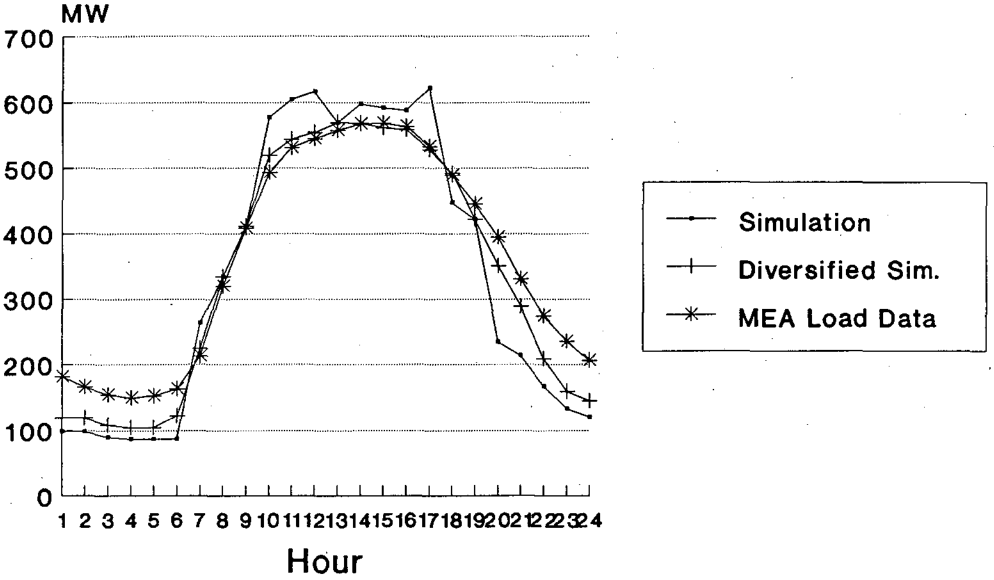
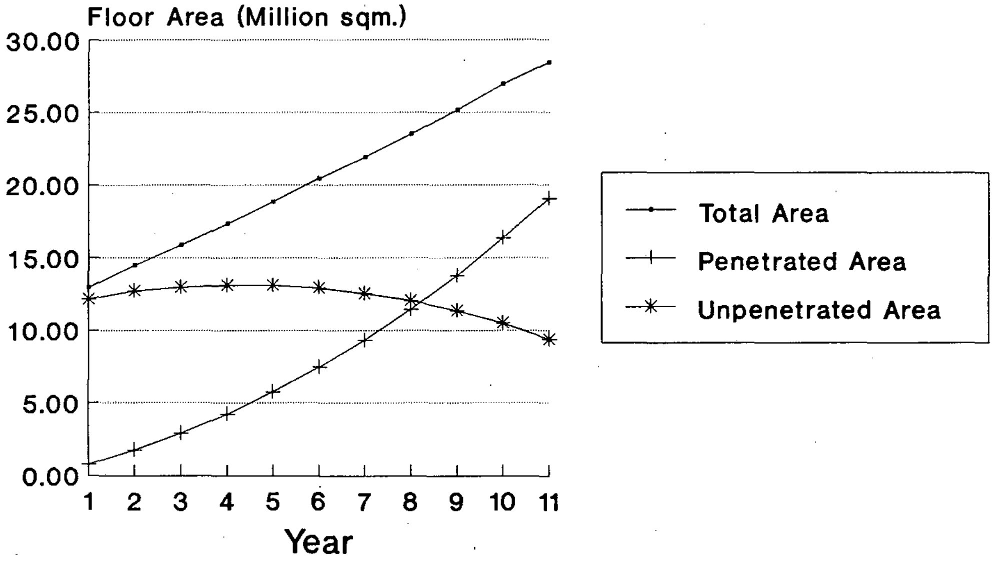
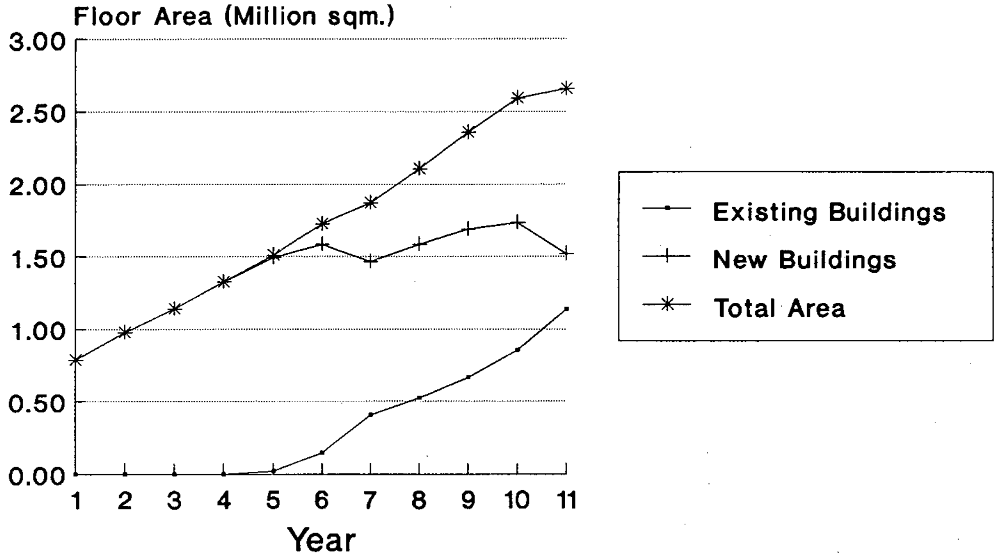


Figure 4H.
Cumulative Conservation Penetration in Thai Commercial Sector



Building Energy Standard,
67% Penetration Scenario

Figure 4I.
Yearly Conservation Penetration in
Thai Commercial Buildings



Building Energy Standard,
67% Penetration Scenario

Figure 4J.
Thai Office Conservation Policy Cases

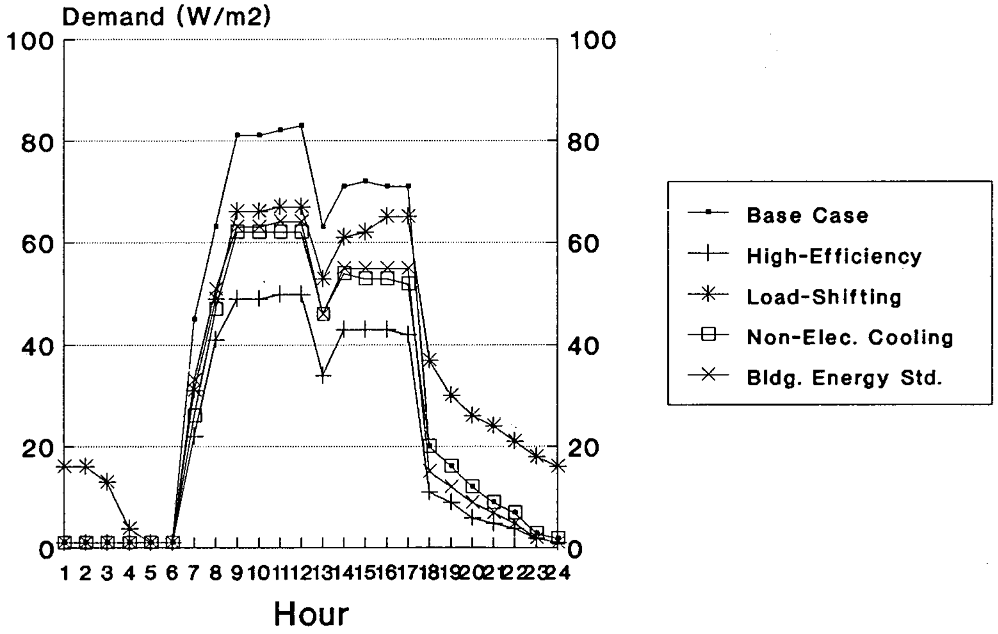


Figure 4K.
Thai Hotel Conservation Policy Cases

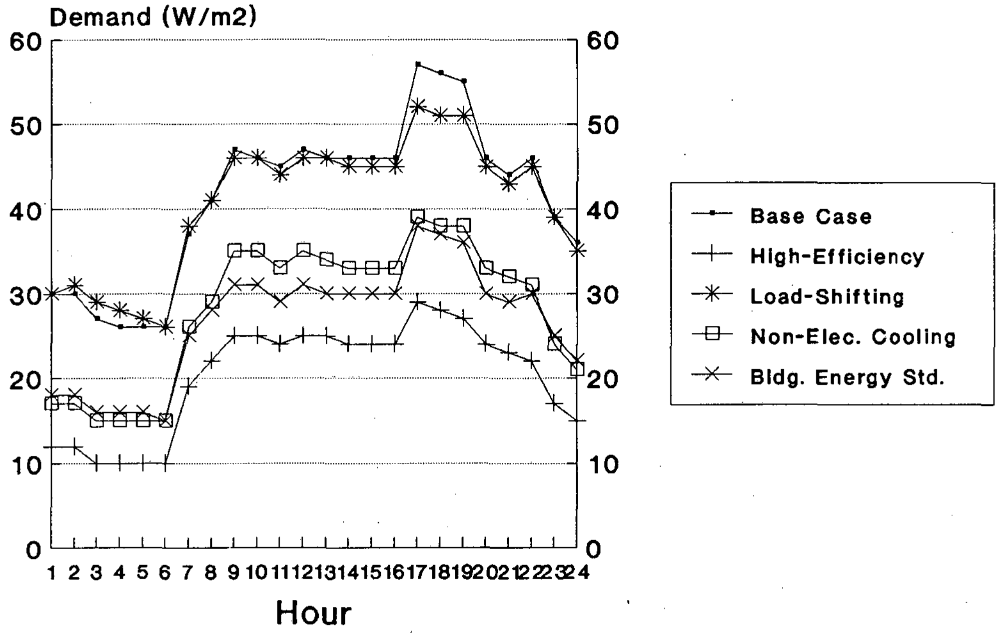


Figure 4L.
Thai Retail Conservation Policy Cases

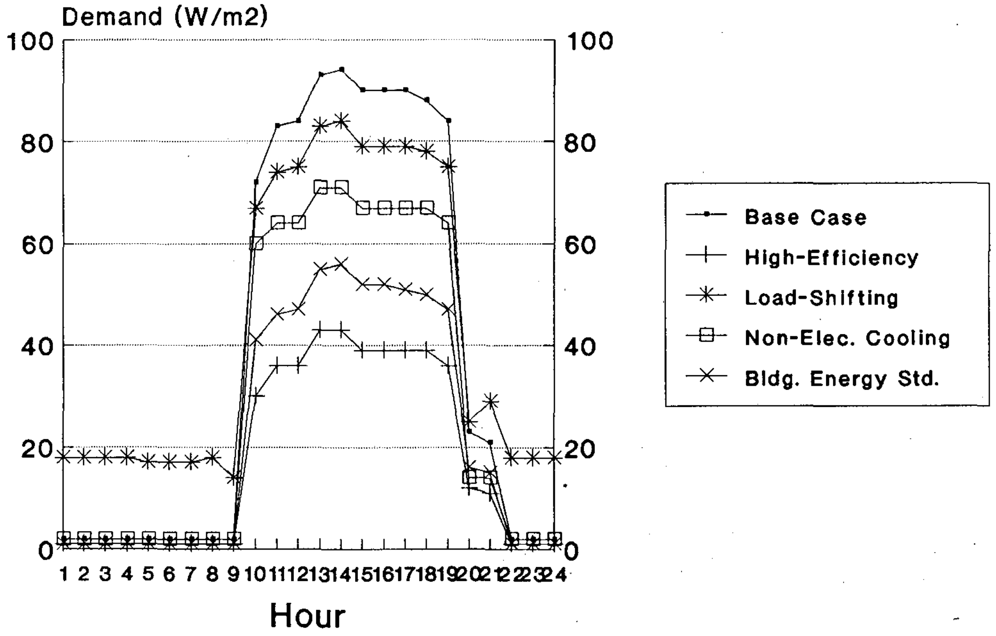
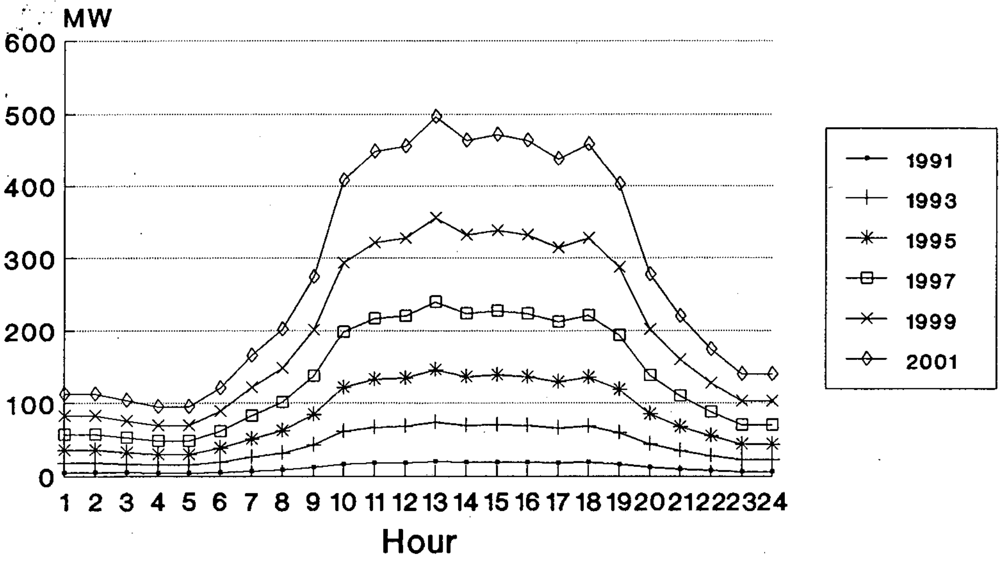


Figure 4M.
Thai Commercial Sector
Load Savings Profile



Building Energy Standard,
67% Penetration Scenario

CHAPTER 5

Towards a Thai Energy Conservation Policy for Commercial Buildings

INTRODUCTION

Preceding chapters have established the potential for conserving electricity in Thai commercial buildings, and have demonstrated how such potential, if exploited, might affect Thailand's power sector. Realization of the electricity conservation potential ultimately will be determined by factors which influence why conservation technologies are not now being adopted, and how they might be introduced and adopted with a mix of policy instruments.

Energy efficiency in commercial buildings depends on government action to promote conservation concepts and technologies, and private interest in applying them. Energy conservation and demand management form part of Thailand's energy policy within the framework of economic planning; some of these efforts are already underway [NESDB 1985, 1986, 1988]. Most of the actions proposed in this chapter do not require a large government financial commitment, nor do they require a sustained government effort that would compete with other pressing public demands. Rather, they involve measures such as optimizing prices, adjusting taxes, setting standards, promoting technical demonstrations, etc. Once government has established the favorability of energy conservation concepts by participating in the market, the concepts could be taken up by the private sector.

Policies affecting conservation implementation have both macro and sectoral dimensions. At the macro level, government sets broad policy and wields various economic instruments for generalized purposes. These actions shape the context for, among other things, sectoral level processes, such as the penetration of conservation technologies. While macro policy to unlikely to be guided wholly by concerns of policy impacts on conservation, an appreciation for the linkages could assist such decision making. Policy actions specifically addressed to energy conservation issues naturally take place at the sectoral level. In this chapter we approach these two levels, first presenting sensitivities of the results to changes in the macro policy context, followed by discussion of sectoral policy approaches that could be used to promote energy conservation in commercial buildings.

SENSITIVITIES TO THE LARGER POLICY CONTEXT

The analysis in preceding chapters was built upon certain assumptions that reflect existing conditions or expectations of future conditions. Macro-economic policies to some extent govern those conditions or expectations and they, in turn, influence the results of the analysis. Were the larger policy context to shift, some results also would be likely to change. In this section we discuss some of those assumptions and their probable qualitative impact on results described earlier.

Economic Growth

A forecast of high economic growth underpins the electricity load growth profile envisioned by the Thailand Load Forecast Working Group [1989]. This load profile was used in the base case utility characterization against which conservation scenarios were compared. If instead, lower economic growth occurred, then the savings from the conservation scenarios would remain the same in the absolute, but would constitute a larger proportion of total electricity load and savings. However, power plant deferrals, and hence capital savings might be lower if the base case plan envisioned fewer plants coming on line which might otherwise be deferred. Low economic growth may signal a tight capital market in which case the conservation scenarios would become more attractive due to energy conservation's low capital intensity relative to conventional utility power.

Fuel Prices and Availability

Fuel prices play a role in determining the mix of resources found in the utility's power expansion plan and, hence, the type of plants available to defer with conservation. If the prices of all fuels changed equally, then no change would be expected in the configuration of the power plan, but the production cost savings from the conservation scenarios would rise or fall in concert with the fuel prices. If, however, the fuel prices changed relative to one another, then some changes in the power development plan might occur. In this instance, one would not expect the total deferred capacity to differ, except where unit sizes differed as a function of fuel price regimes. This subtle effect would likely reduce the reserve margin gains due to the conservation scenarios where unit sizes of deferred plants were smaller, and visa versa.

In a related manner, the availability of domestic fuels plays a role in the power development plan resource and technology mix. To the extent that natural gas and lignite enjoy favorable pricing treatment (i.e., their prices to the utility may reflect production costs more than world energy markets), new discoveries of either or both fuels would likely lead to an increase in their respective shares in future generating mixes, and a similar effect on conservation scenario results as in the case of fuel prices cited above.

Electricity Prices

Electricity prices affect the cost-effectiveness results of the conservation cases: the higher the prices, the more attractive conservation, and visa versa. Electricity prices were assumed to remain constant (in real terms) over the period of the analysis. To some extent, electricity prices in Thailand reflect the political climate surrounding urban/rural issues. While prices are uniform throughout the country for like customer classes, Bangkok electricity users nevertheless subsidize upcountry users since the costs of serving the latter are higher. Should a preference for greater economic efficiency develop and electricity pricing change to reflect the actual costs of service, then this net transfer from urban to rural sectors would decline. This change would also lessen the price incentive for commercial consumers in Bangkok to conserve electricity. Under these circumstances, the utility might stand to gain from conservation relative to expected revenue decreases due to lower prices in the Bangkok commercial sector. Conversely if greater equity was sought, then the opposite trends could be expected. On a more subtle level, the conservation scenarios themselves may force changes in the structure of electricity prices to allow the utility to recover embedded costs.

Cost of Money

The discount rate used in calculating some of the economic measures, such as cost of conserved energy, affects results. A seven percent real discount rate was assumed; higher discount rates generally degrade the cost-effectiveness from a consumer's standpoint. The choice of discount rate also affects the calculation of capacity deferrals from conservation scenarios. Using higher discount rates would de-value capacity deferrals further out in time in the power plan, forcing larger near-term deferrals. Lower discount rates would have the opposite effect.

Non-Utility Power

The current five-year Thai economic development plan promotes private investment in power projects [NESDB 1985, 1986, 1988]. At present, the utility does not incorporate privately-produced power into its expansion planning. If some of the public power investment now envisioned by the utility is instead shifted to the private sector, then one obvious impact on the conservation scenarios would be that fewer deferrable plants would be available (assuming it was not desirable to defer private power). A less obvious effect could be a shift in the utility cost structure due to the non-utility power and the nature of their contracts with the utility.

Purchased power from outside of Thailand is currently limited to small contracts with Laos and Malaysia. Should the substantial hydro resources of Indochina be developed and sold to Thailand, then this could alter the plan for domestic power development. Conservation scenarios, under this altered context, could then be used to further offset domestic plant construction, or to displace imported electricity. It is difficult to speculate on the impact of such a context on the scenarios, but the determining factors would include the nature of the purchased power contracts (e.g. timing of deliveries, cost, etc.) the amount of purchased power available, and the degree to which Thailand was willing to rely on outside sources for its electricity needs.

THE MEANS TO CONSERVATION

In this discussion of the means for achieving energy efficiency in commercial buildings, we focus on three categories of sectoral policy measures -- energy pricing, incentives, and information -- and combinations of these measures. Where appropriate, discussion refers to the conservation scenarios presented earlier in this paper. Since the scenarios each embody a technology or conservation strategy, they lend themselves to certain types of policies or program approaches. In selecting certain policy approaches over others we have applied the following criteria with the Thai context in mind:

- Feasibility -- Is it possible to apply such an instrument to such a problem?
- Acceptability -- Is the approach politically and culturally palatable?
- Effectiveness -- Is there a high probability of success by using the policy instrument?
- Economic Efficiency -- Is this the optimal means to achieve the desired effect?

This list of criteria is not exhaustive but rather is intended to serve as a basis to which other criteria may be added.

Energy Pricing

Electricity Prices. Prices inform consumers of the value of any commodity; electricity is no exception. As a general rule for a utility, tariffs should reflect financial realities, namely explicit costs of operation and embedded costs, and should anticipate in some sense the cost of future expansion [Collier 1984]. Economists have advocated marginal cost pricing as being the most efficient pricing approach. However, because the method depends on the cost regime of a given utility at any particular point in time, this approach may result in under- or over-recovery of costs [Kahn 1988]. There is also the matter of correctly allocating costs among customer classes. It would appear from the analysis in the previous chapter that the Large Business customer class in Thailand currently "pays its way". Efficiency improvements within the class lead to a net loss for the utility, while electricity prices are high enough that savings from conservation investments accrue quickly to the consumer. However, the structure of Large Business tariffs is probably sub-optimal as is demonstrated in the example of the application of thermal energy storage (TES) systems for load-shifting. While beneficial from the customer's standpoint, the load-shifting scenarios were not beneficial, in terms of load impacts or economics, to the utility. This imbalance arises because the tariff structure rewards the customer for levelizing demand even if the shift away from their peak is towards the system peak. For the case of load-shifting strategies like TES, the utility would be better off imposing time-of-use (TOU) rates. Otherwise customers may invest in and operate load-shifting technologies to the utility's disadvantage. U.S. utilities, given favorable price signals, have found commercial customer TES systems beneficial.

Presently, the high rates to Thai commercial customers are a strong price signal and yet, these customers do not conserve. In fact prices are high enough that the utility revenues would decrease with efficiency improvements. Nonetheless, the utility could raise rates to make up the loss in revenues; so long as monthly bills of participants are not increased, customers would likely remain satisfied. Additionally, higher rates would promote further efficiency investments.

Alternative Fuel Prices. Currently natural gas is marketed only to the electric utility and some industrial users, but not to commercial customers. If natural gas (whose recoverable quantity from the Gulf of Thailand is still uncertain), were to be made available for use in commercial buildings instead of or in addition to the current users, (depending on the size of the resource), overall primary fuel efficiency would be enhanced. Less total gas is consumed with the use of gas-engine chillers featured in our non-electric cooling scenarios, than by conventional electric chillers driven by 29% efficient gas "peaking" turbines through the power grid [Ogden 1988].

At gas prices currently paid by EGAT, gas-engine chillers are cost-effective in commercial buildings as we showed earlier. Prices to commercial customers would undoubtably be higher because of the costs of a distribution network. Since peak cooling times and the utility peak period do not wholly coincide, less primary fuel may or may not be consumed under the non-electric cooling scenarios. As Thailand industrializes and the utility peak moves more towards the cooling peak in commercial buildings, the overall fuel savings argument will become more compelling. The threshold beyond which gas used in thermal chillers would be less cost-effective than electricity would depend on the relative fuel prices as well as developments in cooling equipment performance.

Incentives

Financial. Government can, through various economic inducements, catalyze conservation investment. In addition, government has the power to correct fiscal policies which tend to favor energy supply over energy conservation. For instance, while the utility in producing electricity is exempt from corporate taxation, any firm which instead conserves electricity and thereby increases its profit, also increases its tax burden [Mahasandana 1989]. Appropriate tax credits, deductions, or favorable depreciation schedules for investments in efficient equipment could be applied to compensate for this added burden and encourage conservation.

Other financial instruments available to the government are loans or outright grants. The Industrial Finance Corporation of Thailand does have a small program of this type offering loans at a few percentage points below the market interest rate, but this has not brought many applicants.

One way for government to "leverage" their monies is to provide incentives to private energy service companies (ESCOs) who assess and then make conservation investments themselves in buildings owned and occupied by others. ESCOs make their income through the savings reaped by the investment, usually shared with the building owner by contractual arrangement. Thus, under ESCO arrangement, the building owner incurs no risk, needs no knowledge about conducting energy analysis, and at the same time benefits from lower energy bills. Society gains from a reduction in energy consumption, and from the employment that such businesses generate. Government could encourage an ESCO industry with favorable tax treatment or with seed capital. Once such a service industry was proven viable, private capital would likely follow the government lead, and the government incentives could be reduced or retracted.

Import Duty Exemptions. Energy-efficient equipment or products could be given special consideration in setting import tariffs. Equipment for space cooling and lighting, and advanced window glass are examples of promising categories to target. Eligible items might include: efficient chillers, fans, pumps, and motors; efficient light-bulbs, solid-state ballasts, luminaires, and lighting controls such as motion sensors and photo-optic dimmers used for daylighting; and glass with low-emittance coatings. It is highly unlikely that excepting these devices from import duties would measurably affect government revenues, and such an exception could very well improve the overall balance of payments by reducing imports of the fuels (e.g. oil or coal) from current levels required for these same commercial end-uses. The marketability of many of the measures incorporated into this study's High-Efficiency scenarios would be enhanced by tariff reductions.

Information

Outreach. Government can play a key role in disseminating information about conservation opportunities, approaches, technologies, analytical tools, and past failures and successes. Information can be distributed through media advertising, through general brochures and technical manuals, and through seminars and workshops for engineering and architectural professionals. Energy audits, already a part of government conservation efforts, can be used as a source of data for a database on energy use in commercial buildings. This database could be maintained and periodically published with analyses to inform policy makers and the public of typical energy use in commercial buildings and trends over time.

Demonstrations. Government could sponsor demonstrations of the most promising conservation technologies in actual buildings as models for owners, architects, engineers, and others. In exchange for financing the efficiency measures, government energy analysts could monitor the energy performance of the demonstration projects to gather solid evidence of savings (or lack thereof) that can then be incorporated into the commercial building energy database and distributed.

Awards. Thai architects win accolades for aesthetics but rarely for practical energy-efficiency. Government, perhaps in partnership with the Association of Siamese Architects, could offer energy-efficiency awards to lend prestige to practical energy-conscious designers.

Design Assistance. While there are architects and engineers who can and do perform energy analysis of building designs, many others might engage in the practice if design assistance were available. Such assistance could be provided through an office funded by the government and staffed by practicing private architects and engineers working part-time to answer questions concerning design concepts, analysis tools, construction materials, and energy efficient products. This too could be done in cooperation with professional societies.

Combinations of Means

Conservation policy measures could be applied individually but probably would lead to a greater effect if applied in combination. As conditions change, so does the basis for effective response to specific policies. A package of policy measures might remain robust through inevitable change in the market over time despite variability in the effectiveness of individual measures through those changes. Below we illustrate some examples of policy combinations that pertain to our conservation scenarios. Our list is not intended to be exhaustive.

Standards. An effective way of overcoming some intractable market failures is to set minimum energy efficiency standards for buildings, equipment and appliances (E&A). The building energy standards scenarios presented earlier are no more stringent than what has already been proposed; they differ only in so far as they represent varying penetrations depending on whether they are applied to new or existing buildings, or both in combination. In fact, the efficiency levels attained by full compliance (i.e., 100% penetration) with the proposed standards are two-thirds as high as the high-efficiency case of comparable penetration. Standards for new commercial buildings are now under consideration as voluntary guidelines. Voluntary guidelines may have little effect as illustrated earlier in the 3% penetration scenario which produced only minor gains. On the other hand, mandatory standards requiring enforcement may do no better.

Building energy standards could be incorporated into the existing mechanisms for new construction permitting that currently require certain minimum standards for structural and fire safety. But to enhance cooperation, particularly with regard to existing buildings, compliance could be rewarded with positive incentives such as lower electricity tariffs or alternatively, negative incentives such as penalties or fines for non-compliance. Singapore followed this approach by combining both types of incentives in its energy standard policy towards existing buildings [Wong 1984]. The policy allowed owners who complied to take a tax credit amounting to 40% of their retrofit expenditures. Additionally, after a two year grace period, a 20% surcharge on electricity use was imposed on those who failed to comply, increasing to 50% after five years.

The Singapore experience reveals the policy tactic of adapting the incentive over time. In the case above the penalty started modestly and became progressively more stiff; it could just as well begin with a positive incentive, and transform into a negative incentive. Such a scheme also might be structured, as some in the U.S. have advocated, such that penalties are assessed for failing to meet the standard, and rewards are given for exceeding the standard's requirements, yielding a revenue-neutral balance [Koomey 1989]. If these symmetrical incentives were calculated on a sliding scale of efficiency, this approach would have the benefit of encouraging greater efforts towards efficiency. As the efficiency norm shifted upwards, so too could the stringency of the standard (in order to maintain revenue-neutrality), resulting in an ever-greater stock efficiency. Having incentives based on a sliding efficiency scale would necessitate that calculation procedures be simple, accurate, and easy to verify.

Equipment and appliance standards can be worthwhile for the simple reason that minor improvements in materials, workmanship, and componentry can significantly reduce energy usage with only marginal or negligible cost increases. Manufacturers often do not make those small investments themselves for fear of losing market share. The appeal of standards is that manufacturers are put on equal "energy-related" footing and can then compete on the basis of other features. E&A standards entail a different implementation process than building standards because they deal with identical, manufactured products instead of one-of-a-kind buildings. They may in fact be easier to administer by nature of having fewer entities to account. Whereas building energy standards require calculation procedures to test compliance, E&A usually comply with standards by testing in laboratories using agreed-upon procedures. Both the laboratories and procedures would need to be established in order for E&A standards to be implemented in Thailand.

Like building standards, E&A standards have one drawback in that they do not encourage efficiency improvements beyond the minimum level of compliance. Government can, in addition to enforcing standards, insist that energy performance information about E&A be provided in a uniform manner to prospective customers. Such a labeling program in the U.S. has been credited with making consumers aware of the energy tradeoffs of different products, and creating greater demand for energy-efficient appliances.

High efficiency. The high efficiency scenarios incorporate technologies, most of which would be more readily adopted in the market if a combination of policy measures were applied. Import tariff exemptions or reductions, and income tax breaks would promote the choice of efficient cooling and lighting equipment, and design assistance would help ensure that the systems incorporating these equipment were better integrated with and other architectural design options.

Thermal Storage. Along with the change to TOU electricity prices, TES adoption has been enhanced in the U.S. by grants or loans for the incremental costs of the system, as well as by assistance in design of the overall cooling system.

Utility Involvement. Utility programs have been a powerful vehicle for conservation in U.S. buildings. The most successful of these employed combinations of measures in so-called integrated programs [Nadel 1990]. Utilities already have a commercial relationship with their customers and they have access to large sources of capital. U.S. utilities, usually in response to pressure from regulatory agencies or consumer and environmental groups, have been successful in promoting conservation with the whole gamut of instruments already discussed. Utility programs in the U.S. have: provided loans and grants for all or part of the cost of energy-efficient equipment; provided design-assistance for novel approaches such as cooling systems utilizing TES for load-shifting; conducted energy audits; and generated incentives through the tariff structure.

A challenge to securing utility involvement in Thailand is that, like U.S. utilities a decade ago, they see their mission as producing energy, not saving it. Conditions have changed for some U.S. utilities, though, and many now embrace conservation programs as an appealing alternative to building central-station power plants. The reasons they give for involvement in conservation include lower-cost, more flexibility in terms of capital costs, financing requirements, environmental quality, timing and scale of activities, and improvement of relations with customers and regulators {Hirst 1986]. Another benefit to utility involvement is that by contributing to the conservation process, they have more control over the outcome.

To the extent that the Thai utility sees its mission as maximizing revenues or return on investment, energy conservation in the commercial sector is not in their interest, as our analysis has shown. However, if it is deemed of national importance to reduce the capital requirements of the power sector without jeopardizing energy services and development potential, and the utility adopts this concern, then the utility may indeed find conservation programs an attractive way to promote energy services since conservation demands approximately one quarter the capital investment of equivalent power plants. The Thai utility, as a quasi-public agency, could become the lead agent of national energy conservation policy, and subsume most or all of the policy measures thus far accorded to government.

CONCLUDING REMARKS

Current policies for energy supply and demand management in Thailand provide a valuable framework for improving efficiency in the commercial sector. In light of the current economic and political context as well as foreseeable changes in these circumstances, our analysis demonstrates that energy conservation can play a larger role in overall planning and development in Thailand. Policy measures in this chapter illustrate various means government could use to increase energy efficiency in the commercial sector. These means, selected for their feasibility, acceptability, effectiveness, and economic efficiency could be implemented individually or in combination. Packages are more compelling for their resiliency relative to individual measures. By encouraging a lead role by the utility in energy conservation, Thailand can help promote a balance between public capital demands, environmental quality, commercial competitiveness, and power sector viability. In sum, energy conservation in commercial buildings helps to achieve a strong position for pursuing other national objectives.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720