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TECHNOLOGICAL AND ECONOMIC ISSUES IN BUILDING ENERGY USE

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Part I
ENERGY EFFICIENCY AND BUILDINGS IN WEST AFRICA

1. Introduction

Demographic projections indicate a rapid growth in the cities of West Africa over the coming several decades. The buildings constructed during this period will be operated well into the next century and the amount of energy they use will be an important dimension of the economies of the region. There is an opportunity for the nations of the region to insure that buildings be designed and operated in an efficient manner, freeing valuable capital and electricity supply and distribution infrastructure for other uses.

Commercial buildings are one of the largest single users of electricity in West Africa. According to the recent Proceedings of the 1981 ECOWAS Energy Symposium (National Academy of Sciences, 1982),

Some 40 percent of the electrical energy produced in the ECOWAS countries is reportedly used for air conditioning, lighting, and water heating. Appropriate architectural design and new building materials could reduce electricity consumption.

A single office building of 25,000 square meters would typically require electricity at an average rate of several MWe. In some ECOWAS states, several such buildings could alone consume five to ten percent of the total installed capacity. In a region where the total installed generating capacity is on the order of 4000 MWe, rapid growth in buildings will require an associated growth in electricity generation, transmission and distribution. Since much of the power generation is from thermal plants using imported oil, the costs of buildings which are highly consumptive of energy and also inefficient are substantial. The electricity which is consumed for inefficiency in buildings is not available for productive uses. In addition, higher fuel consumption places a higher burden on the balance of payments. Energy conservation can therefore be thought of as a source of fuel whose marginal cost is a fraction of that of conventional fuels or electricity, and whose price does not rise with time.

There is now considerable experience to suggest that energy efficient building design and operation can have a financial payback in a very short time, sometimes within a few years. Moreover, buildings which have been designed and operated for a high degree of energy efficiency routinely achieve comfort levels at least as high as in non-efficient buildings. Energy efficiency means doing more with less, not doing without.

2. Energy Efficient Buildings - Traditions and Current Concerns

Throughout the world, indigenous traditions of architectural design have evolved over hundreds and even thousands of years. These designs, usually the result of long periods of trial and error, have resulted in building designs
which use local materials and technology to provide shelter and comfort to inhabitants. Such techniques have included the use of massive building materials in hot, dry regions to moderate the often extreme temperature swings between night and day. In hot, humid tropical regions, the use of designs to capture breezes and shade the building from direct sunlight is well known.

For the most part, these indigenous techniques have evolved for residential structures and some public buildings. The large contemporary office building is a distinctly twentieth century product which has its roots in Europe and the United States. Much of the development of such buildings has been in cold or temperate climates. Beginning in the 1950's, large numbers of similar buildings have been constructed in regions of the world very different in climate and culture from the environments in which they initially evolved. The result has too often been the construction of buildings ill-suited to either tropical or hot arid regions, where the inadequacies of the design have been "overcome" through massive amounts of air conditioning.

During the last decade, there has been an increasing movement among architects throughout the world towards environmentally-conscious building design, towards rediscovery and application in contemporary form and technique many of the ancient principles which evolved for indigenous building forms of the past. The approach has not been the literal adoption of such practices in new buildings, but rather the incorporation in a rational way of energy-efficient and climatically-sensitive design techniques. The result has often been buildings which are not only efficient in energy use and comfortable for their occupants, but visually exciting and interesting to work in.


There is no simple all-encompassing policy which a country or region can adopt to insure that buildings will be designed, built and operated in an energy-efficient manner. One of the authors (JMW) was involved in the design of legislation in California in 1972 whose purpose was to establish energy performance guidelines and standards for new commercial (non-residential) buildings in the state. It took several years of hard work by various committees made up of architects, engineers, building contractors, equipment suppliers, building code officials, and other professionals, to develop an approach which was more or less workable. It is fair to say that the policy process was a turbulent one. There is no reason to think that it would necessarily be simpler anywhere else.

At the same time, the economic imperatives for improving the energy performance of existing buildings and designing more efficient new buildings have had an effect in California, and elsewhere in the United States and Europe, as well as increasingly in other parts of the world. There have been several key elements to achieving increased energy efficiency, both in new and existing buildings. These include:

- Economic incentives for building owners and operators to increase energy efficiency;
o Availability of usable design tools and calculational procedures for use by architects and engineers.

o Availability of straightforward means for building code officials to verify compliance with energy efficient design and operation procedures. (Unless the rules have workable means for implementation, they will not be implemented. This is common sense and also common experience throughout the world.)

4. Obstacles to Implementing Energy-Efficiency for Buildings

There is a variety of obstacles to widespread practice of energy efficient design and operation of buildings. These will have to be addressed in development of any effective energy efficiency programs. Some of the important institutional issues include:

o Building owners rarely experience the buildings they create. Consequently, the owners tend to be less concerned than they might about operating costs, especially when these can be recovered through rents.

o First costs tend to be more important than life-cycle building costs, even for many buildings which are owned by the original builder (including the government).

o Adequate experience and design tools are not widely available in some regions, and design professionals can rarely afford the costs of training themselves in energy-efficient design practice.

o There are inadequate policy guidelines for establishing energy-efficiency criteria, and

o There are insufficient economic incentives for builders and designers to develop energy-efficient buildings, even when there is a clear imperative at the national level.

A central issue is the development of national policy which translates the need for energy efficiency at the national level into economic imperatives at the level of the individual building designers, builders, owners and operators. Some of the means for accomplishing this include in the following:

o In Singapore, building owners are required to occupy a major fraction of the building for several years before they can become an absentee landlord. This has the effect that the owners pay the operating costs and therefore experience the degree of efficiency (and comfort) of the building.
Investment policies, such as interest rates on building loans and energy efficiency tax credits can be related to life-cycle costs as opposed to first costs. Until the investor also feels the need for energy efficiency, it will not become a widespread reality.

In the past, architects have generally not been concerned with energy conservation and efficiency. There is a need for the training of architects, engineers and building operators in how to save energy. As part of the training, there needs to be design handbooks and manuals appropriate to the specific locale where the building will be located, which can be used in a familiar way by design professionals and operators.


While the use of simple "rules of thumb" in building design can contribute to energy efficiency, considerably greater gains can be obtained through the use of computer-assisted design. However, there are important practical problems involved in the implementation of computer tools for building design. Most architects and engineers, in all countries, remain unfamiliar with the use of computers as design tools. By contrast, the use of guides and manuals containing calculational procedures (including easy to use nomographs or graphical methods) for sizing air conditioning equipment, optimizing window area and building orientation, determining effective use of insulation and so forth could quickly become a familiar and widely used procedure.

An important contribution to the goal of the diffusion of energy-efficient building practices in West Africa would be the development of a set of design manuals for the major climatic zones of the region, for use by architects, engineers and building managers. These manuals would be designed for straightforward use by these professionals, but their development would require the use of a computer program such as DOE-2, incorporating the necessary hour by hour information on temperature, humidity, insolation, etc. for the various regions of interest.

Such a manual could be developed within an appropriate institution in West Africa, with participation by professionals from the various ECOWAS member states. Through collaborative arrangements with design professionals who have developed and used these computer-based tools, it would be possible to implement the programs, train people in their use, and develop the series of manuals which would be periodically updated and refined through actual use of these in the local design process.

An important associated activity would be the establishment of a suitable data base of climatic information, both from available records and, as needed, through new measurements. Buildings designed and operated using the manuals could be monitored to compare predicted and actual energy performance. Through such monitoring, the effectiveness of the manuals could be determined and the manuals improved as necessary.

6. Computer Simulation of Building Energy Use
The thermodynamics of commercial buildings is a complex subject. Even the best and most comprehensive of available computer models which attempt to simulate the energy performance of such buildings are only approximations and their use is as much an art as it is a science. They really must be considered as imperfect tools to be used in the craft of energy efficient building design. Yet the complexity of these buildings really requires computer analysis in order to quantify the energy use and cost implications of various design possibilities. Because of the large number of interacting variables for a building, the modification of one (such as lighting level or window area on a specific exposure) affects the response of the building to changes in others.

Our intention is not to go into the details of energy efficient design techniques for large buildings. These are covered in an extensive literature and in the User Manuals for the various computer programs currently available. In Part II, we provide a discussion of one specific computer-based tool which is now in wide use internationally for evaluation of energy use in complex buildings. This program (DOE-2) could be used as discussed above to help develop a practical energy efficiency design guide for commercial and public buildings in West Africa.

Part II

The DOE-2 Building Energy Use Analysis Program

1. Motivation for Development

DOE-2 is a public domain computer program which can be used to explore the energy behavior of proposed and existing buildings and their associated heating, ventilation and air conditioning (HVAC) systems. Incorporating mathematical models (called algorithms) and utilizing hourly weather data, DOE-2 calculates the hour by hour performance and response of a building whose description has been provided by the user. In addition, DOE-2 can produce an economic analysis of the energy use and the costs and benefits of making alterations in design.

DOE-2 is intended to be used by architects, engineers, and others who are concerned with the energy analysis of buildings and with the consequent economic implications. Although energy analysis was initially the concern of the mechanical engineer alone, it is now recognized that the architect also has tremendous influence on the energy usage of buildings. Before the rise of modern HVAC equipment, the architect was the primary determiner of the energy consumption of a building and architectural building design included consideration of how the occupants were to be sheltered and kept comfortable. Use of passive solar heating and ventilating was a primary concern. With the rise of cheap and apparently abundant energy and with the development of technologically clever delivery systems, it became less incumbent on the architect to be as energy conscious when designing a building. The secondary HVAC systems could be relied upon to make up for the lack of natural heating and ventilating and to provide a comfortable interior climate. The realization that
energy is no longer plentiful and inexpensive has re-awakened the architect to
the need to consider energy analysis in building design.

The same need has arisen for the mechanical engineer. Since the aim is no
longer simply to provide a system which will meet the heating and cooling
loads of the building, but also to do that efficiently so that the loads are
met with the least expenditure of energy, the mechanical engineer can no
longer deliberately oversize the equipment to ensure meeting the loads. Over-
sizing usually means the equipment operates extensively in a less efficient
mode. Avoiding this energy waste requires knowing what minimum capacity is
required.

Master carpenters are fond of impressing their young apprentices by
measuring a desired length of lumber by running their thumbs along the board
and making a thumbnail impression at the point where they intend to saw. When
the apprentice measures the mark with a rule, it is inevitably accurate.
Although an architect or an engineer applies more sophisticated techniques in
design, there is in these professions an appreciation — indeed, a certain
amount of reverence — for the ability to sift through the complex considera-
tions that go into the design of a building or a HVAC system and to specify
the dimensions and the components without recourse to detailed computations.
At most the calculations should be limited to "the back of an envelope." To
require more is often perceived as a detriment to good design and the sign of
a failure to be well trained. After all, the person is a designer and not a
calculator!

The energy and economic considerations mentioned above, however, have made
many old "rules of thumb" out of date. The design of energy (and money) con-
serving buildings and systems depends upon attending to the subtle interac-
tions of a large number of design features. When one is designing without the
safety of over-sizing, the energy consumption becomes sensitive to the many
variables which describe the design. To keep track of this large number of
variables, a computer becomes essential.

Even if a hand calculation were possible, to consider a number of alterna-
tives would require a number of hand-done analyses. The tedium of such a task
is what a computer is designed to alleviate and what a computer allows. The
outgrowth of making parametric runs, as the recalculation of many alternatives
is called, is the development of a more informed "rule of thumb," and this is
also a contribution that the computer can make. Among many other other
options, with the computer fine-tuning of sizing can be made, the efficacy of
hot gas bypassing can be assessed, and various alternative energy storage
strategies can be explored.

It was to create such a computer tool that in 1976 the Energy Research and
Development Administration (ERDA), which later became part of the US Depart-
ment of Energy (USDOE), began the development of what has become the DOE-2
program. Although several national laboratories have been involved in the
program over the last seven years, the work is now concentrated at Lawrence
Berkeley Laboratory. The purpose of this project has been to create, test,
document and maintain a user-oriented, public domain, computer program that
will enable architects and engineers to perform design studies of whole-
building energy use under actual weather conditions. The development of this
program, which in its successive public generations has been known as Cal-
ERDA, DOE-1.4, DOE-2.0, and, finally, DOE-2.1, has been guided by several objectives:

1) that the description of the building by the user be in quasi-English so that the input can be read and understood easily by non-computer scientists;

2) that, when available, the calculations be based upon well-established algorithms, i.e., the calculational procedures used should be acceptable to the engineering community;

3) that it permit simulation of commonly available heating, ventilation, and air-conditioning (HVAC) equipment;

4) that the computer costs of the program be minimal; and

5) that the predicted energy use of a building be acceptably close to measured values.

All of these objectives have been met and the DOE-2.1B version of the program is now available from the National Technical Information Service for less than $2500. Considering that the development costs for this program have exceeded $10 Million, this has to be a great bargain.

2. **General Description of DOE-2**

Energy use analysis of buildings involves four principal steps.

First is the calculation of heat loss and gain to the building spaces and the heating and cooling loads imposed upon the building HVAC systems. This calculation is carried out for a space temperature fixed in time and is commonly called the Loads calculation. It answers the question: how much heat addition or extraction is required to maintain the space at a constant temperature as the outside weather conditions and internal activity vary in time and the building mass absorbs and releases heat.

Second is the calculation of the energy addition and extraction actually to be supplied by the HVAC system in order to meet the possibly varying temperature set-points and humidity criteria subject to the schedules of fans, boilers and chillers, and to outside air requirements. This calculation results in the demand for energy that is made on the primary energy sources of the building. This step, called the Systems calculation, answers the question: How are the accumulative heat extraction and addition rates modified, when the characteristics of the HVAC system, the time-varying temperature set-points, and the heating, cooling and fan schedules are taken into account?

Third is the determination of the fuel requirements of primary equipment such as boilers and chillers, and of the energy production of solar collectors, etc., in the attempt to supply the energy demand of the HVAC systems. This Plant calculation answers the question: how much fuel and electrical input is required to feed the secondary HVAC system given the efficiency and operating characteristics of the plant equipment and components.
The fourth step evaluates the costs of equipment, fuel, electricity, labor and retrofit components against the alternative of investing the money in other ways. It answers the question: Is the expenditure of funds for energy conserving materials and systems cost effective, when compared with alternative systems and investment possibilities?

The first three steps are illustrated in Figure 1, showing the flow of energy. The different methods of and accuracy in performing these steps differ essentially in the degree to which the mathematical models chosen to simulate these steps match the actual world. The continually varying outside weather conditions, the movement of people, and heat from lighting and equipment inside the building lead to a cooling and/or heating requirement that is always changing — not only in total amount — but in its distribution in the building. Even if there were valid mathematical models for all of the simultaneous processes, an exact calculation of the dynamic response of the structure would not be possible. Every energy analysis program must then make approximations and assumptions.

In particular the continuous time dependence of phenomena is approximated by making the calculation in small discrete time intervals. The objective of more refined calculational procedures is to simulate the heating and cooling loads and system responses by making the time interval as small as is practicable. DOE-2 is programmed to compute the building behavior in hourly intervals which permits a more realistic approximation than energy analysis programs which use an average day per month.

Such a small interval — implying 8760 steps in a calendar year — would be impossible without the use of advanced computer methods, especially when it is realized that careful design may require the calculation to be made several times to test alternatives. The long history of development of such calculational procedures has been justified on the basis that more accurate calculations will give improved analysis of life cycle costs of buildings, more precise sizing of equipment and more carefully controlled operation of the primary and secondary HVAC systems.

3. Uses for the Program

Because of the flexibility of its input, the DOE-2 program can be of assistance in many applications, especially the consideration of energy conserving alternatives and in building and systems design:

1. Energy Conservation Studies
   a) Effect of the thickness, order and type of materials and orientation of exterior walls and roofs;
   b) Effect of thermal storage in walls and floors and in water tanks coupled to HVAC systems;
   c) Effect of occupant, lighting and equipment schedules;
d) Effect of intentionally undersized secondary HVAC systems and central plant equipment.

e) Effect of intermittent operation, such as the shutdown of HVAC systems during the night and/or on weekends and holidays or for any hour during the day;

f) Effect of reduction in minimum outside air requirements; scheduled use of outside air for cooling;

g) Effect of internal and external shading, tinted and reflective glass;

i) Effect of off-peak heating or cooling of buildings on peak heating or cooling electric demand;

j) Effect of load management, load deferral and load limiting on space environment and on energy use.

k) Active solar collector/storage systems for heating and cooling;

1) Heat recovery strategies to eliminate wastage of rejected heat.

2. Building design studies

a) Initial design selection of the basic elements of the building, primary and secondary HVAC systems, and energy source;

b) Evaluation, during the design stage, of specific design concepts and modifications, including optimal system zoning, optimal control strategies, and optimal systems selection;

c) Evaluation, during construction, of contractor proposals for deviations from the construction plans and specifications;

d) Monitoring the operation and maintenance of the finished building to provide the greatest return on energy investment;

e) Analysis of existing buildings for cost-effective retrofits;

f) Analysis of electric load management schemes as applied to single buildings or multi-building complexes.

g) Comparison of loads and equipment selections using design day features versus those that result from weather tapes;
4. Examples of Applications of DOE-2

DOE-2 is now being used in at least 12* countries around the world by architects, engineers, and government agencies. Unfortunately, most of the applications have been made for private firms and the proprietary results are generally not available. The studies made by researchers have been published and include such topics as the optimal combinations of glazing properties as a function of climate and the use of diesel engine driven emergency power generating system for peak shaving in buildings. Other studies have been undertaken specifically to test how well the predictions of DOE-2 compare with field measurements.

Some results of these studies are presented in Figures 2-6. Figure 2, for example, compares the measured hourly temperature in a test cell with the DOE-2 predictions using two different algorithms. With what are called custom weighting factors it is difficult to discern any differences between the measurement and the prediction, while the other algorithm makes predictions off by as much as 70°F (4°C). In comparisons with actual occupied commercial buildings DOE-2's predictions were within 15% -- quite an achievement given the poor data that exist on operating and occupant schedules. Work done by Oak Ridge National Laboratory on residential properties showed that in unoccupied homes DOE-2 came within 1% of describing the monthly utility bills.

What might be of especial interest here is a study in which one of us (RBC) is currently engaged in Singapore. This is an ASEAN (Association of SouthEast Asian Nations) project sponsored by USAID. The purpose of the project is to assist the Government of Singapore in the development of energy standards for buildings. As a part of that project we have been making parametric DOE-2 runs on a proto-typical office building, trying out various strategies and looking for the sensitivity of the building's net energy use to these changes.

One of the consequences of this study is the discovery by the American researchers that the climate and latitude of Singapore gives rise to building energy use considerations for which our experience in a more temperate climate and larger latitude did not prepare us. This has alerted us to the fact that energy conservation strategies are not immediately transferable from Europe and America to equatorial Africa. For example, it never occurred to us that one had to be conscious of solar heat gain through northern windows! Also the lack of a need for heating removes a strategy for using the heat generated by air-conditioning equipment. Most unsettling was the realization that when the outside temperature does not fall below 75°F (24°C), one cannot use outside air for cooling. We have had, therefore, to look in much more detail at how energy is used in buildings on the equator and to see what was important.

* These include (in addition to the United States), Austria, Canada, Chile, France, Italy, Japan, Kuwait, New Zealand, Peoples Republic of China, Singapore, and Sweden.
What was discovered was that reducing lighting levels, both by using more efficient ballasts and lamps and by dimming lights in areas where they were not needed, made it possible to reduce building energy use by about 20%. Reducing the ventilation air quantity from 10 cfm per person (4.7 l/sec-person) to half that amount could save another 10%. Shading of windows could produce 10 to 15% savings and moving to variable volume fan systems contributed another 10%. These figures are preliminary, dependent on the building taken as the base, and represent savings taken one at a time. It is often the case that the result of two energy conservation measures is less than the sum of the effects of each one individually. The reason for this is that perhaps best illustrated by an extreme example. As mentioned, reducing lighting levels will save energy. So also will reducing the size of the windows. If, however, one removes all the windows, one will not be able to see if all the lights are also turned off! A less extreme example is illustrated in Figure 7 where the energy consumption in peripheral zones is depicted with and without overhangs over the windows and with and without daylighting. If the effects were simply additive, the figures would be parallelograms.

It should be stressed again that these results may or may not be transferable to the African environment. It is necessary to use building prototypes from this region, to take into account the change in latitude and, especially, the details of the climate. The operation of DOE-2 requires hour by hour weather data for the site being analyzed. One might guess that there are similarities between Singapore and Lomé, but even here we would like to study the situation more closely.

5. Possibilities for Africa

We have earlier suggested that an ECOWAS supported research center could use the DOE-2 program to develop commercial building design manuals for West Africa. Let us now describe in a little more detail our motivation for approaching the conservation of building energy use in West Africa through such a device. As sophisticated as DOE-2 is, it has an inherent limitation. Before a building can be modeled on the computer, its configuration and detailed construction parameters must be defined. On the other hand, by that time in the design process the energy consumption of the building is already quite well determined. If buildings are to be designed to be energy efficient, the architect must be influenced before he has drawn the first line. What is required is a number of energy-conscious "rules of thumb" that the architect can use as he contemplates satisfying his clients needs.

These "rules of thumb" are necessarily climate and region dependent; what saves energy on the coast may not do so well in the highlands. Areas with dry, cool nights have possibilities that do not exist when the humidity is high. These design manuals, therefore, will be tailored to each climatic region.

What kind of things do we imagine to be in the manuals?

- Curves showing the effect on energy use of the orientation of a building.
Diagrams showing the dependence of energy consumption on building configuration.

Trade-offs between wall-to-window ratio and lighting requirements.

Costs and benefits of roof insulation for various roofing types.

Impact of building color and surface roughness on building energy use.

These are just the beginning of a long list of design issues that can affect how much energy the building will use.

By centralizing such work, a number of economies of scale could be achieved. It would not be necessary to devote scarce resources to acquiring many computers and training many duplicate staffs. Once proto-typical buildings were defined, they could be used over and over again for different climates and regions by changing the weather tapes. Perhaps at some later stage it would possible to use the facilities in the design stages to refine predictions of energy use for large building projects. Finally and perhaps the most exciting facet of this suggestion, by undertaking such a project ECOWAS could show the world how valuable such manuals could be. As far as we know, comparable projects are not yet happening anywhere else.

6. Acknowledgement

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Figure 1. Schematic of Energy Flows in a Building

Figure 2. Los Alamos National Laboratory Test Cell Measurement Comparison with DOE-2.1 Predictions

Source: R. Curtis (1981) (See Fig. 1 citation)
Figure 3. DOE-2 Predictions of Energy Use Compared With Measured Data for A Residential Building

ACES CONTROL HOUSE
SUMMER 1978
MED. EFFICIENCY H.P.

Source: J. W. Michel (22 Nov., 1982), (Informal Memorandum), Oak Ridge National Laboratory
Figure 4. DOE-2 Energy Use Predictions Compared With Actual Utility Data

Reference run - DOE-2 prediction versus gas utility data for restaurant.
Figure 4-a

Reference run - DOE-2 prediction versus electric utility data for restaurant.
Figure 4-b

Reference run - DOE-2 prediction versus total energy utility data for restaurant.
Figure 4-c

Figure 5. DOE-2 Predicted Fuel Oil Consumption - the Mariott Hotel, Boston, MA

Source: Citation for Figure 4
Figure 6. DOE-2 Predicted Electricity Consumption - Mariott Hotel, Boston, MA

Source: Citation for Figure 4.
Figure 7. Energy Savings in Singapore with Overhangs and Daylighting

(WWR = Wall-to-window ratio; SC = Shading Coefficient)
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