# ECAP
## An Energy and Cost Analysis Program for Microcomputers

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**ABSTRACT**

ECAP, a microcomputer program which performs a comprehensive energy and cost analysis on the energy-related systems of building designs is presented. The structure, capabilities, and limitations of the program are discussed. The unique and innovative features of the program, particularly the solar-heat-gain and daylighting routines, are emphasized. Recent improvements in the user-friendliness

### 1. INTRODUCTION

The Tennessee Valley Authority (TVA) continues to develop, as part of its Design Guidelines for Energy-Efficient Buildings (1), a microcomputer program which performs a comprehensive analysis of the energy-related systems in buildings. It is called ECAP, for Energy and Cost Analysis Program.

ECAP is an energy- and economics-analysis tool intended to help architects, engineers, and designers assess the merits of architectural and system-design alternatives in reducing the consumption of purchased energy by commercial buildings. ECAP is a comprehensive design/analysis tool which deals with all of the energy-related issues of building design addressed by TVA's Design Guidelines, most importantly the life-cycle costs of energy for lighting, cooling, heating, and HVAC auxiliaries (and to a lesser extent, in-zone equipment and service hot water). ECAP is based on the modified bin method of building-energy analysis and incorporates enhancements made by TVA to make it simpler to use, more accurate, and more comprehensive in scope. It was designed with the intention that it be easy to use, that it be applicable throughout the design process, and that it be readily understandable and usable by design professionals.

### 2. PROGRAM STRUCTURE

ECAP is a menu-driven, structured program. Four principal program modules are available from the main menu:

1) Edit Module
2) Run Module
3) Print Module
4) Install Module

I will discuss the Run Module first to provide a clearer understanding of the program.

#### 2.1. Run Module

The Run Module performs the energy analyses on the building. Three types of analyses are performed:

1) Zone Analysis
2) Building Analysis
3) Economic Analysis

The zone submodule performs what are commonly called loads and system analyses on a single zone. The building submodule gathers output from several zone analyses and performs a plant simulation on all of them, and computes the annual and life-cycle costs of energy for the entire building or project. The economics submodule takes key output from two or more building analyses and performs an economic comparison of each with the first, yielding five indices of economic merit. Each submodule creates disk files containing pertinent data for later use by the other program modules.

The Run Module is designed such that the user may submit up to sixteen runs at once and have them execute in "batch mode" without further interaction by the user. These sixteen runs may be any mix of zone, building, or economic analyses. The screen continuously shows the status of the batch submission and remains "animated" to guard against infinite loops and other "locked up" conditions. All sixteen runs must use weather data for the same location which is specified at the same time as the sixteen run-file names.

#### 2.1.1. Zone Analysis

The input file for the zone analysis contains descriptions of the zone, its air-side HVAC system, its operating characteristics, and schedules. This submodule first reads the zone input file and preprocesses some of the input for subsequent use. It then performs a simplified ASHRAE sizing calculation for both heating and cooling apparatus.

It then performs an annual energy analysis of the zone and system loads using an enhanced implementation of the bin method of building energy analysis. It then performs a peak analysis for both a warm and cool condition in each month. (Since the condition which produces the utility peak on the whole building is not known until the plant simulation in the building analysis, both conditions are analyzed here.)

### 2.1.2. Building Analysis

The input file for the building analysis contains the names of the zones to be included in the building, economic parameters, plant-costing parameters, a description of the utility rate structure, and indices for the HVAC plant(s) in the building. In the present version, the user may select either a central plant (all zones assigned to a single plant) or unitary "plants" (each zone has its own plant). This submodule first reads the building input file and preprocesses some of the input for subsequent use. It then gathers and assimilates data from the disk files from each zone analysis and simulates the response of the plant to the assembled loads. It then runs the resulting energy consumption and demand data through the utility rate structure and determines the annual and life-cycle costs of energy consumption and demand for the entire building.

### 2.1.3. Economic Analysis

The input file for the economic analysis contains the names of two or more whole-building analyses and the incremental cost to implement each but the first. The first building is considered the base case. For each subsequent building, five "indices of economic merit" are computed based on the economic criteria supplied to the building-analysis submodule.

## 2.2. Edit Module

The Edit Module enables the user to create or edit input files for any of the three submodules of the Run Module. It uses a tree menu structure to allow the user to enter sets of input in any order. At the data-entry level, a group of variable names and their current (or default) values is displayed on the screen and cursor-controlled editing can be performed. The input forms for ECAP are designed after these input screens for continuity.

## 2.3. Print Module

The Run Module routes raw, unformatted output from the analyses to disk files. The Print Module reads these files and prints them on a line printer in easy-to-read formatted reports. A menu-driven routine allows the user to specify the type of analysis to be printed and to select from a menu of individual reports for that analysis type.

## 2.4. Install Module

The Install Module allows the user to define his/her "system" to the program. A "system" consists of a computer type, printer type, program drive, data drive, and various user-related information (e.g., company name, address, etc.). The user may select from several predefined computers and printers or may specify each feature of any system not on the menu. The Install Module need be run only once; the installation remains in effect until the user wants to change some feature of the installation.

# 3. ZONE MODEL

## 3.1. Envelope Description

There are three major types of envelope components in ECAP--walls, roofs, and floors. Walls are vertical surfaces which may contain windows and doors (which may be any opaque construction). Roofs are horizontal surfaces which may contain skylights. Floors are any construction describable by an equivalent UA value. Input for the zone analysis is structured such that the areas of windows, doors, and skylights are subtracted from their host constructions (ie., walls or roofs). This facilitates parametric analysis in that, for example, the size of a window may be changed without having to change the description of the host wall. Also, each window, door, or skylight may have a multiplier, which also facilitates parametric analysis by allowing the user to change, for example, the number of identical windows in a wall without having to redescribe the entire window and the host wall.

The thermal behavior of a wall is defined primarily by its height, width, U-value, orientation, and color. The first three determine the conductive heat flow through the wall while the last two determine the effect of solar radiation on conduction. This will be discussed in the section on sol-air heat gain. The thermal behavior of a roof is defined by similar descriptors. Roofs are considered horizontal for those characteristics where surface tilt and orientation are significant, such as solar and sol-air heat gain.

## 3.2. Internal Loads

ECAP considers internal heat gain from lighting, occupants, and in-zone equipment (as opposed to HVAC equipment). A latent component is allowed for occupants and equipment. One of the most important aspects of modeling internal loads is reducing and delaying instantaneous heat gain from each source (due to the thermal mass of the structure) so that the loads seen by the space-conditioning equipment during the daytime and nighttime are correct. ECAP performs this "weighting" process internally based on hourly schedules for each internal load, construction weight of the zone, and type of load.

### 3.3. External Loads

#### 3.3.1. Conduction

ECAP calculates conductive heat flow using conventional ASHRAE procedures. ECAP processes the information in the zone input file and produces an overall heat transfer coefficient for the entire zone with units of Btu/hr/$^oF$. This value is multiplied by the difference between the outside and inside temperatures. This value is then modified by the sol-air heat gain which is explained below.

#### 3.3.2. Solar Heat Gain

One of the unique features of ECAP is the way it computes solar heat gain and other phenomena based on the solar resource. It became clear, after researching the bin method, that existing methods of describing the solar resource as a function of outside temperature, as is required by the bin method, were questionable at best. Using DOE2.1A and TMY weather tapes for three cities representative of the TVA region, we generated (for each city) a year's worth of hourly "observations" of total solar radiation and the coincident dry-bulb temperature for nine surface orientations--each 45-degree compass point plus horizontal. We then removed the observations for hours during which the sun was below the horizon. These edited data were then sorted by dry-bulb temperature into ascending order. A percentile analysis was then performed on this data set, adding another variable to each hourly observation--the percentile rank of the solar-radiation value of the observation at the coincident outside temperature. A regression analysis was performed on this data set to yield the coefficients of a biquadratic equation of the form:

$$RAD = A_0 + A_1*T + A_2*T^2 + A_3*P + A_4*P^2 + A_5*T*P \qquad [1]$$

where: RAD = Total (direct + diffuse) solar radiation transmitted through a single sheet of 1/8" glass, in Btu/hr/sf.
T = Outside temperature, $^oF$.
P = Percentile
$A_0$ to $A_5$ = Coefficients

Equation [1] describes the solar resource as a function of both outside temperature and percentile of occurrence. Percentile may be thought of as a degree of severity, 100% being the most severe (ie., clear day), 0% the least. Thus, with a single set of six coefficients, we can describe, for each orientation, the solar resource for an average condition, a sunny peak condition, and a cloudy peak condition by specifying the outside dry-bulb temperature and an appropriate percentile. ECAP currently uses 53rd, 75th, and 25th ercentiles for the conditions mentioned above. hese were empirically derived by comparing the output of several DOE2.1A analyses to the output of the Equation [1].

To calculate total solar heat gain in a zone with glass in more than one orientation, ECAP uses a "master" set of biquadratic coefficients derived from the coefficients for each orientation modified to account for glass area, shading coefficient, and construction weight:

$$B_{io} = (A_{io} * AGL_o * SC_o * SWF_o) \qquad [2]$$

where: i = coefficient subscript
o = orientation subscript
A = orientation coefficient
B = window-adjusted coefficient
AGL = Window glass area, sq.ft.
SC = Shading Coefficient
SWF = Solar Weighting Factor

The resultant window-specific biquadratic equations are added to yield the "master" set of coefficients for the entire zone:

$$C_i = \sum_{o=0}^{n} B_{io} \qquad [3]$$

where: C = "Master" coefficient
B = window-adjusted coefficient
n = number of windows

Now, the solar heat gain seen as a load in the zone can be found from:

$$QSOL = C_0 + C_1*T + C_2*T^2 + C_3*P + C_4*P^2 + C_5*T*P \qquad [4]$$

where: QSOL = Total solar heat gain in the zone, Btu/hr
T = Outside temperature, $^oF$.
P = Percentile
$C_0$ to $C_5$ = "Master" coefficients

The solar weighting factors in Equation [2] were generated from the algorithms used by DOE2.1A and are tabulated in documentation for ECAP.

#### 3.3.3. Sol-air Heat Gain

ECAP accounts for the effect of solar radiation on conduction--the "sol-air" effect--by computing it as a separate load which is added to the conduction load based on temperature differential. While a detailed explanation of the procedure for determining the sol-air load is beyond the scope if this paper, the procedure is similar to that used for solar heat gain in that the coefficients describing the solar resource on each orientation are modified to account for the area and absorptance of each opaque surface (wall, roof, or door). The sol-air load is considered to be instantaneous by ECAP; it is not reduced and delayed (due to the mass of the envelope) between occupied and unoccupied periods.

### 3.3.4. Daylighting

other unique feature of ECAP is its ability to model daylighting strategies using vertical windows and/or horizontal skylights. A daylighting source was created from TMY weather tapes in much e same manner as for the solar resource. 'er, prior to the regression analysis of the ed data set, separate values for diffuse and rect radiation were transformed into values of mens per square foot. The statistical analysis was performed on this data set to yield a biquadratic equation similar in form to Equation ]. A worksheet supplied with ECAP documentation lps the user determine a room calculation factor (RCF) to describe the ability of a window system to supply exterior illumination to a reference point side the zone. The RCF may also be obtained from del studies.

Since daylighting is only effective in reducing ergy consumption if the electrical lighting can reduced in response, the method of controlling e electrical lighting system is important. ECAP allows the user to specify one of several control rategies, the algorithms for which are based on ose in DOE2.1B (2). The **on-off switching** control ll turn the lights completely off when the interior daylighting level exceeds a user-specified otcandle level (at the reference point). The **epped switching** control allows the lights to be rned off in incremental blocks, based on user-pecified control steps. The **continuous-dimming** ntrol allows completely smooth response of the ectric lighting system to interior daylight vel. Finally, the **manual switching** control llows the user to specify the probability that ne in the zone will manually turn off the s when the daylight level exceeds a user-ecified foot candle level. ECAP considers both ask and ambient lighting. Daylighting offsets ly the ambient component.

## 4. SYSTEM MODEL

### 1. Configuration

he generic air-side HVAC system modeled in ECAP's ne analysis is intended to be capable of proximating the performance of most common stems, depending on the inputs describing its omponent parts and characteristics. For example, systems where zone loads are met be a central il, the coil loads found in this simulation may thought of as this zone's share of the central oil load (found in the building analysis). ECAP cumentation contains guidelines for choosing puts to simulate several common system types.

### 4.2. Fan Options

ECAP can model several types of fan control strategies:

- o Constant volume,
- o VAV with inlet vanes,
- o VAV with discharge dampers, and
- o VAV with variable speed motor.

The user may specify that any of these fan "types" either cycle or operate constantly. The heat produced by and the electricity consumed by the fans are computed using algorithms used by DOE2.1A.

### 4.3. System Loads

The algorithms used within ECAP, except those discussed above, are fairly straightforward implementations of those found in References (3) and (4). In some cases, they have been simplified either to adapt them to the bin method from hour-by-hour methods or to reduce the complexity of user input.

## 5. PLANT MODEL

The plant simulation which takes place in ECAP's building analysis is derived almost entirely from algorithms used by DOE2.1A. The user may choose from the following menus of eight cooling plants and ten heating plants.

**Cooling Plants**

1) Packaged terminal heat pump (HP) or air conditioner (AC)
2) Commercial packaged terminal HP or AC
3) Residential HP or AC
4) Open centrifugal chiller with cooling tower
5) Open reciprocal chiller with cooling tower
6) Hermetic centrifugal chiller with cooling tower
7) Hermetic reciprocal chiller with cooling tower
8) No cooling plant

**Heating Plants**

1) Packaged terminal HP
2) Commercial packaged terminal HP
3) Residential HP
4) Electric Furnace
5) Gas Furnace
6) Oil Furnace
7) Electric hot water boiler
8) Fossil hot water boiler
9) Electric steam boiler
10) Fossil steam boiler

Once a plant type has been specified, ECAP internally chooses the corresponding set of parameters to describe the energy input to the plant (as a function of both part-load-ratio and outside dry-bulb and wet-bulb temperatures), the electrical input to associated pumps and fans, capacity adjustment for non-ARI design conditions, and other performance characteristics.

As mentioned previously, the current version of ECAP has only two options for zone-to-plant assignments--either all zones on one plant, or each zone on its own plant.

## 6. ECONOMICS

ECAP computes the annual and life-cycle costs of both energy and demand as well as the initial cost of HVAC equipment.

Based on a user-specified utility rate structure and a minimum-billing procedure typical of the TVA region, ECAP determines the annual cost of both energy and monthly demand. Since ECAP uses annual bin weather data, the bin analysis it performs is inherently blind to individual months. Therefore, ECAP divides the annual energy consumption of the building by twelve and runs that number through the rate structure to determine the average monthly energy cost, which it multiplies by twelve to yield annual energy cost. Demand costs for the entire building are computed for each individual month and added to yield the annual demand cost. ECAP cannot model time-of-day demand billing since time-of-day dynamics are not possible with the bin method.

Life-cycle costs are computed using common economic formulae based on user-specified economic parameters including discount rate, time horizon, and energy escalation rate. ECAP allows separate escalation rates for electrical energy, electrical demand, and fuel energy.

ECAP costs HVAC equipment using an algorithm used by DOE2.1A. This equation uses known equipment sizes and costs, supplied by the user, to determine the cost of the HVAC plant sized by ECAP. This equation recognizes that equipment cost is not a simple linear function of equipment size.

The economic-analysis module performs an economic comparison of two or more building analyses. Five indices of economic merit are computed:

1) simple payback ratio,
2) discounted payback period,
3) net life-cycle savings,
4) savings-to-investment ratio, and
5) return on investment.

Each of these indices has a different purpose and may be applied as called for by the situation at hand. Indices 1), 3), and 4) are simple calculations, while indices 2) and 5) are more complex and are solved iteratively.

## 7. REPORTING FEATURES

It is our intention that ECAP be as useful as possible to building designers. An important measure of the usefulness of an analysis tool is the degree to which it facilitates the identification of specific energy-related problems which can be addressed in the design process. With this in mind, we designed the ECAP reports to be as detailed as practical, and to track the component loads as far as possible through the analysis. This enables the designer to identify the source of major energy-related problems in a project, and to gauge the potential effect of design changes on each component.

## 8. APPLICABILITY

Because ECAP is being developed primarily for use within the TVA region, many of its routines and supporting data are specific to that region. However, many of the routines rely on user input which might be modified in the absence of more suitable input. For example, ECAP's solar-heat-gain routine uses a biquadratic equation derived from a statistical analysis of a TMY weather tape. The form of the equation, however, is such that setting some of the coefficients to zero will produce a bilinear equation (straight-line function of two variables). A "spreadsheet" program and some other source of solar data could be used to produce suitable coefficients for such an equation with relative ease.

Also, most supporting data used by ECAP is placed in ASCII disk files which could be easily modified by any user with a friendly text editor. The weather data used by ECAP is one example. The format for these files is available from the author on request.

## 9. MICROCOMPUTER SPECIFICATIONS

ECAP is written in code which is compatible with both Microsoft's BASIC-80 interpreter for CP/M, version 5.2 and later, and IBM's BASICA interpreter. A microcomputer with 64K of random-access memory (RAM), an 80-column screen, two disk drives with a capacity of about 100K each (minimum recommended), and an 80-column printer are required. ECAP is distributed by TVA in ASCII files on disk and may be modified (by those willing to do so) for other BASIC dialects and the file-naming requirements of other operating systems. Disks are available for the IBM-PC (and compatibles) and many CP/M formats.

## 10. REFERENCES

(1) Arnold, George, Robert S. Briggs, and Ben Garlington. "The Development of TVA's Energy Design Guidelines Manuals", Progress in Solar Energy, Vol. 6, American Solar Energy Society, 1983, p.747.

(2) Winkelman, F. C. "Daylighting Routines in DOE2.1B", Supplement to DOE2.1A Engineers Manual, USDOE, 1983.

(3) ASHRAE, 1977 Handbook of Fundamentals, Atlanta, 1977.

(4) Carrier Corporation, System Design Manual, Part 1 - Load Estimating, Syracuse New York, 1960,68,72.

## 11. ACKNOWLEDGMENTS

The author would like to acknowledge the significant contributions of George Arnold, Rob Briggs, and Bruce Reeves in conceiving, implementing, reviewing, and testing many of the routines used in ECAP.

## 12. DISCLAIMER

The United States, TVA, and their agents and employees make no warranties or representations, express or implied, with respect to the accuracy of ECAP results or to the suitability of the analyzed building and support systems based on these results. ECAP is in the public domain, is currently under development and testing, and has NOT been thoroughly debugged or validated. All results should be carefully reviewed before being implemented or acted upon.

NOTE: At press time, several portions of ECAP are being modified. While this paper reflects most of those modifications, the specifications and features of the released version may differ slightly from those presented here.

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:::::::::::::::::::::::::::::::::: (ECAP 2.0) ::::::::::::::::::::::::::::::::
:  Energy and Cost Analysis Procedure                        Version 2.0   :
:  Tennessee Valley Authority                                  June 1985   :
:.......................................................................:

              :::::::::::: MAIN PROGRAM MENU ::::::::::::
              ::                                        ::
              ::  E) EDIT or create a data file         ::
              ::                                        ::
              ::  R) RUN one or more ECAP programs      ::
              ::                                        ::
              ::  P) PRINT reports for previous analysis ::
              ::                                        ::
              ::  I) INSTALL Terminal, Printer, and User ::
              ::  ..................................    ::
              ::                                        ::
              ::  Q) QUIT ECAP                          ::
              ::                                        ::
              ::::::::::::::::::::::::::::::::::::::::::::
                Press E,R,P,I, or Q:
```

FIGURE 1 - ECAP MAIN PROGRAM MENU

```
:::::::::::::::::::::::::::::::::: (ECAP 2.0) ::::::::::::::::::::::::::::::::

          :::::::::::::::: MAIN EDIT MENU ::::::::::::::::
          ::                                              ::
          ::  Z) Edit or Create a  ZONE input file        ::
          ::                                              ::
          ::  B) Edit or Create a  BUILDING input file    ::
          ::                                              ::
          ::  E) Edit or Create an ECONOMICS input file   ::
          ::  ........................................    ::
          ::                                              ::
          ::  Q) QUIT ECAP                                ::
          ::                                              ::
          ::  R) RETURN to Main Program Menu              ::
          ::                                              ::
          ::::::::::::::::::::::::::::::::::::::::::::::::::
            Press Z,B,E,Q, or R:
```

FIGURE 2 - ECAP MAIN EDIT MENU

```
:::::::::::::::::::::::::::::::::: (ECAP 2.0) ::::::::::::::::::::::::::::::::

    :::::::::::::::::::::::: ZONE EDIT MENU ::::::::::::::::::::::::
    ::                                                              ::
    ::  A) General Data (do first)   :  K) HVAC System              ::
    ::  B) Walls                     :  L) Controls                 ::
    ::  C) Roof                      :  M) Window Assignments       ::
    ::  D) Floors                    :  N) Door Assignments         ::
    ::  E) Windows                   :  O) Skylight Assignments     ::
    ::  F) Doors                     :  P) Schedules                ::
    ::  G) Skylights                 :  ........................    ::
    ::  H) Occupants                 :                              ::
    ::  I) Lighting/Daylighting      :  R) RETURN to Main Edit Menu ::
    ::  J) Equipment and Hot Water   :  S) SAVE Data to disk file   ::
    ::                                                              ::
    ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
      Press A-P,R, or S:
```

FIGURE 3 - ECAP ZONE EDIT MENU

```
::::::::: (ECAP 2.0) :::::::::::::::::::::::::::::::::::::::::::::::::::::::
: Module: (EDIT)     : Subsection: (WALL 1 OF 4)                             :
: Section: (ZONE)    : Work File: (WBNTOA.EZI) (WBN Temp Office Bldg A)      :
:.........:..........:.......................................................:
      (Variable)    : (Current Value)
       WALLNAM$     :SOUTH WALL (type 6)
       HTWALL       : 9
       WDWALL       : 225
==)    UWALL        : .0833
       AZ           : 180
       CLTDW        : 37
       COLW         : .83
       SWFAVocc     : .52
       SWFAVuno     : .24
       SWFPKw       : .59
       SWFPKc       : .23
                    :
                    :
                    :
                    :
Enter UWALL--------)0.05
....................:........................................................
Actions) SPACE: Arrow down   BKSP: Arrow up   TAB: Edit mode   ESC: to Menu
```

FIGURE 4 - TYPICAL INPUT SCREEN