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Proposed format for organizing the study of building energy economics

. . . Because of the demands of an affluent society and readily available, competitively priced fuel sources, major efforts of the engineering community were concentrated on performance parameters rather than energy economics . . . A point has now been reached in our society where this concept of energy economics will soon be a lasting criteria in the design of any energy conversion system. Thus, a new subscience is imminently required—the applied science of energy economics . . .

Because of the revolutionary advances in building environmental technology of the last four decades, approximately one-third of all energy resources consumed today is converted directly or indirectly for the purpose of environmental control in building spaces. During this period of rapid technological growth, the demands of an affluent society and the ready availability of competitively priced fuel sources led the engineering community to focus its major efforts on performance parameters in preference to energy economics.

However, competitive market pressures have recently led some practitioners to explore methods of evaluating the economics associated with a building's energy systems. One segment of the industry, system design, is concerned with the development of specific techniques for applying these evaluations. As it becomes increasingly evident that the world community is approaching the intersection on the curves between available energy resources and immediate demand, these techniques will provide the nucleus for a new parameter in building systems design: energy economics.

The concept of energy economics should be a primary criterion in the design of any energy conversion system. If it is to be useful to more than a limited number of informed specialists, its guidelines must be based upon specifically defined evaluation functions, which past efforts have not provided. The following discussion is proposed as the groundwork for the applied science of energy economics for building systems.

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The building environmental system

A diagram of the building environmental system is shown in Fig. 24-1. The box to the extreme left represents the space to be occupied or conditioned. The space experiences a heat loss or gain depending upon numerous factors familiar to all practitioners. The rate of this heat loss or gain at selected maximum conditions is defined as the heating load or cooling load, respectively. The letter E shown at various points around the diagram represents points of energy flow into or out of the system. The arrow designations are used to denote the direction of energy flow. Note that arrow, E_1, is double headed, i.e., a point at which energy can flow in either direction is the load and in the context of this subject is the *block load* on the building. If the building consists of more than a single space, it is conceivable that heat will flow into the building system at one point and out at another; the net of these flows is the block load.

The terminal delivery system and terminal control system blocks are, in many systems, either interchanged in the relative locations shown on the diagram, or, in some cases, integrated into a single complex entity.

Thermal energy flows from the space into the terminal systems, or from the systems into the space, at a rate and quantity equal to E_1, thus maintaining the desired space conditions.

Energy required to motivate the terminal delivery systems is illustrated by E_2. The terminal control system is the point or points at which the conditioning of the air takes place, i.e., where the psychometric problem is solved. The energy which flows into and out of the terminal control system is made up of load energy (E_1) which can enter or leave; input thermal energy distributed from the high-level source system; leaving thermal energy distributed to the low-energy source system; and terminal distribution system motivating energy E_2.

The high-level source is made available to the system at a level above the space temperature and the low-level source system provides a sink at a level below the space temperature. From the standpoint of energy flows, it is quite common that within the terminal control system, energy will flow from the high-level distribution system into the low-level system, bypassing the space under usual operating situations. Thus, if the direction of E_1 is from the control system to the space (net heat load), the flow of energy from the high-level source may exceed the value of E_1, the excess

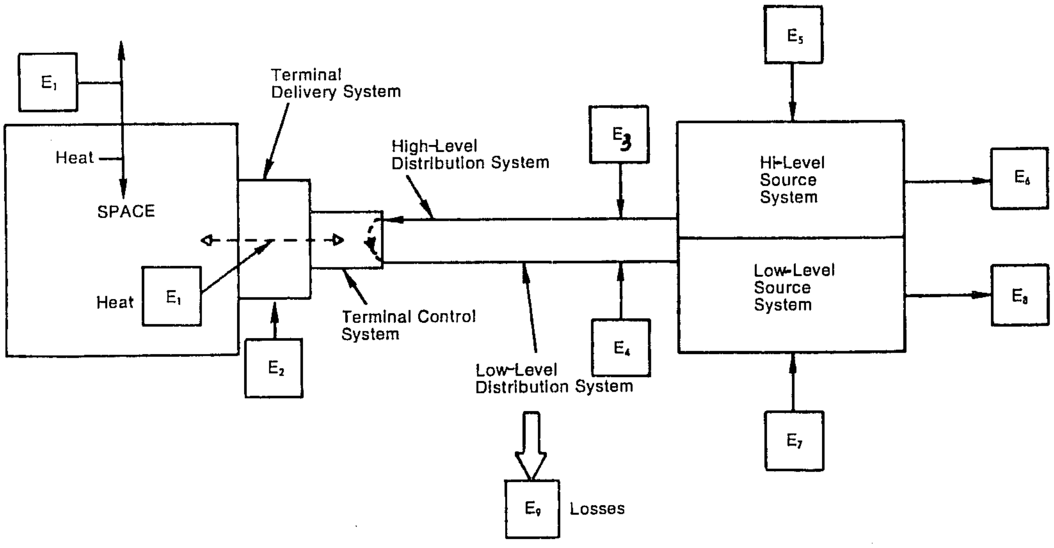

Fig. 24-1.

Table 24-1. Summary of evaluation functions.

	Function	Symbol	Units	Description
Energy functions	Specific building cooling load	β_c	Btuh/sq ft	Building block cooling load/gross area
	Specific building heating load	β_h	Btuh/sq ft	Building block heating load/gross area
	Specific system cooling load	π_c	Btuh/sq ft	Cooling system design load/gross area
	Specific system heating load	π_h	Btuh/sq ft	Heating system design load/gross area
	Specific electric power (cooling)	κ_c	kW/ton	Cooling system electric demand/system design load
	Specific electric power (heating)	κ_h	kW/MBH	Heating system electric demand/system design load
	Specific thermal power (cooling)	τ_c	MBH/ton	Cooling system thermal demand/system design load
	Specific thermal power (heating)	τ_h	MBH/MBH	Heating system thermal demand/system design load
Power functions	Specific thermal energy	ϵ_t	MBtu/sq ft	Annual input thermal energy/gross area
	Specific electric energy	ϵ_e	kW-hr/sq ft	Annual input electrical energy/gross area
	Energy constant	C_e	Btu/kW-hr	Fuel input to generate usable electric energy
	Summary specific energy	Σ	MBtu/sq ft	$\epsilon_t + C_e (\epsilon_e)$

representing a quantity of energy flowing into the low-level system.

Energy flowing into or out of the distribution system may enter or leave at the terminal system or the source systems. Inputs E_3 and E_4 represent energy required to motivate the distribution systems.

The high-level source system converts available energy at the building to a useful thermal form. In the commonplace context of fossil fuel conversion, E_5 represents fuel input plus the energy to drive the feedwater system, the combustion apparatus (fuel pumps, F.D. fans, etc.); E_6 represents such items as stack, radiation, transformer, and friction losses.

The low-level source can be either a refrigeration system or a direct transfer mechanism to a temperature sink lower than the space. In the former, the heat removed from the lower temperature sink is that moving from the *terminal control system* into the low-level distribution system. One component of E_7 represents the external energy source to motivate the transfer, and E_8 represents the "output" energy from the refrigeration machine. Other contributing components of E_7 are the auxiliary refrigeration system loads: condenser water pumps, condenser fans, cooling tower fans, oil pumps, refrigerant pumps, control power, etc.

The remaining component, E_9 represents the irreversible losses which do not enter into the defined systems.

Power functions

One goal of energy economics is to provide evaluation functions for use by building systems design practitioners. The first of these functions is the *specific building load, β.* There are two Beta functions, β_h and β_c, representing specific building heating and specific building cooling load, respectively, in units of Btuh/sq ft. β_h is the design block net heat loss for the building and β_c is the design block cooling load for the building. These functions are calculated by determining accurately the block heating and cooling loads and dividing by the gross building area. The significance of this function is that it represents a major input into the ultimate building energy consumption and, although it may appear to be noncontrolled or independent input value to the environmental systems designer, it is definitely a controllable function as far as the building design team is concerned. The unit area is selected on the assumption that, beyond a minimum comfort height dimension, people use area, not volume, for habitation.

Those aspects of building design which effect the Beta functions include enclosure materials (walls and roofs); enclosure area per unit floor area; fenestration systems and areas; lighting levels, volume, occupant density, and ventilation rate per unit area; weather and climatic conditions; building orientation, program, and use schedules; and indoor design conditions.

It is evident that the essentially noncontrolled input variables, given a building use program and geographic location (or site), are weather and climate. All the rest are controlled inputs, established by the building design team. In this particular function the electrical designer can control the lighting level input and the architect the remainder, with the exception of the ventilation rate, which is under the control of the environmental systems designer. From the standpoint of energy economics, *ventilation rates must be established on the basis of contaminants*; e.g., general ventilation rates must be set on the basis of cfm per person rather than per unit area. For other contaminant types, such as cooking apparatus and systems, efforts must be sought to reduce exhaust volumes to an absolute minimum.

The Beta functions are power units—not energy units. They establish the *rate* at which thermal energy enters or leaves a space. Furthermore, the two functions are not additive, since the power and energy value of a unit of high-level energy is not equal to the value of a unit of low-level energy.

The specific system loads

The specific system loads, or Pi functions, like the Beta functions, are expressed in units of power per unit area (Btuh sq ft), and consist of two nonadditive components, π_c and π_h, representing cooling power and heating power, respectively. The Pi functions are defined as the maximum coincident heating and cooling demands (or loads) that the high- and low-level *source* systems will see. Design aspects which affect the Pi functions include Beta functions, performance parameters (control tolerance of temperature and relative humidity), terminal control systems, and distribution systems power to fluids.

The Pi functions are a measure of the maximum rate at which energy will flow into and out of the source systems from the distribution systems. To illustrate the relationship between Pi and Beta functions: If a building program consisted of one room with one control zone, and the system were 100 percent effective the Pi and Beta functions would be equal. Although this is not the case with most actual building systems, in the practice of building energy economics, every effort should be made to minimize the difference between the two functions.

Insofar as the terminal control system is concerned, it will follow in most cases that the smaller the decrement between the Pi and Beta functions, the more efficient the system will be in reduced load energy consumption.

A comparison of this decrement is defined as the terminal system efficiency, in which

$$\eta_{TC} = \frac{\beta_c}{\pi_c} \times 100$$

$$\eta_{TH} = \frac{\beta_h}{\pi_h} \times 100.$$

Specific system electric power function

The Kappa functions (specific system electric power), and K_c and K_h are defined as the ratio of the electrical power input per unit of cooling power system capacity and per unit of heating capacity, respectively. K_c is expressed in kW/ton and K_h in kW/thousand Btuh (kW/MBH).

K_c is determined by adding the input electric power usually represented by E_2, E_4, and E_7, on Fig. 24-1. These include in addition to refrigeration drives, the auxiliary or parasitic loads listed below. (These auxiliary loads, additive to obtain K_c do not all have the same value when converted to the ultimate energy analysis. Thus, although they are all contributors, each must be considered separately by the systems designer.)

- *Supply and return fans* in commercial air conditioning systems have been found to range from less than 0.1 kW/ton to as high as 0.5 kW/ton. Of all the contributors to the Kappa function, the fan systems because of their high specific power requirement and extensive hours of use, should be the primary target for energy reduction. Two variables which affect the fan power requirement are the quantity of air circulated and the air system pressure. The quantity (cfm) should always be established at the minimum possible level to achieve acceptable performance. Efforts at minimizing the total system air flow must be accompanied by careful attention to effective air distribution methods.

Fan system pressure provides a broader area of control over the specific system power. The most common cause of high fan system pressure requirements has been the high-pressure or high-velocity distribution systems. There are two reasons for such systems: pressure needed for terminal unit control and restrictive space requirements. The designer can, in the application of energy economics, assign a quantitative value to each of these requirements. In most cases the value of the space saved by the high-velocity system is much less than the value of the energy used. Thus, from the standpoint of energy economics, high fan system pressures should be avoided where possible.

- *Chilled water pumping systems*—Like fan systems, the chilled water and heating water pumping system specific power requirement is a function of the flow rate and the pressure drop; also, like the fan systems, the water distribution systems are essentially continuous operation loads, thereby contributing significantly to the ultimate energy usage. Pressure losses in the systems have been fairly well established by the economics of piping systems and heat transfer surfaces. Thus the most readily controlled variable is the flow rate. Since the flow rate is a function of the system temperature range, it follows that, in the design of hydronic systems, the maximum possible temperature range should be taken at all times. In larger systems, the advantages of variable flow rates with load variations should also be considered. If load reductions are achieved by reductions in flow rather than temperature range, significant energy savings can be realized. An additional advantage of the longer temperature rises and the resulting decreased flow rates is that the investment cost of the system is reduced because of smaller pipe and pump sizes.
- *Condenser water pumping systems*—The first effort at optimizing energy use in the condenser water system is the selection of the most effective sink. This has a significant effect on the prime refrigeration energy required. Once this is done, the flow rate of the condenser water system is fairly well fixed by machinery availability and economic considerations. Like the chilled water system, the other variable contributing to the specific power is the pumping head. This head is created or established by the dynamic pressure drop through the condenser, in the piping system, and in system nozzles, and the static lift in the system. The most common cause of high condenser water system power requirements has been overcirculation, i.e., a miscalculation of the required head when selecting the pump, and an excessive power requirement due to the resulting mismatch of system curve versus pump curve.
- *Cooling tower fans*—Aside from performance and capacity requirements, the selection of the cooling tower should be made on the basis of space required, physical arrangement or configuration, construction material, cost, and specific power requirement. All of these parameters are interrelated, but product literature and resulting application have historically ignored the specific power requirement. A search of this literature reveals that towers with the lowest power requirement are often the least costly and constructed of the most desirable materials. Additionally, careful study of control logic schemes, although not reducing the specific power requirement, can significantly reduce the energy consumption of the cooling tower systems.
- *Air-cooled condenser fans* must be considered in the same manner as cooling towers. Generally the selection is more complex, since, with a given ambient temperature, efforts to minimize compressor horsepower will result in increased condenser fan power. Since the condenser fan system in many applications sees a full load throughout compressor operation, the energy analysis indicates a considerable contribution to the ultimate consumption by the specific electric power contributed thereby. As with the cooling tower, efforts in control logic should be aimed at reducing fan energy during periods of reduced load or below design ambient temperatures.

- *Control power*—Although the least significant contributor to specific electric load, the control power requirements cannot be altogether ignored by the systems designer. A simple guideline in the application of pneumatic systems is that continuous bleed-type controllers should be avoided wherever possible. As mentioned above, many currently available terminal devices employ fan system pressure for terminal control power. If this feature leads the designer to select a high-pressure fan system, the fan horsepower burden must be recognized as a control power contributor. *In this type of system, the specific power consumption can be most significant.*
- *Refrigeration system drives*—The refrigeration drives, if electric, are generally the largest single contributor to the specific system electric power function. Although design parameters other than energy economics may lead designers to the selection of refrigeration systems with excessively high specific power ratings, the penalties in energy and power must be recognized and justified.

The specific power requirement is not necessarily a linear function with annual energy consumption, but its computation will lead to areas of concentration for reducing the operating hours of the machinery or achieving more effective reduced load energy reduction.

The K_h function, the specific heating system electric power, like the K_c function, is determined by adding the high-level system auxiliaries and the primary electric energy input when the latter is used as the prime source of thermal energy. The auxiliary loads to be considered in the K_h function include fuel pumping drives, forced draft fans, induced draft fans, electric fuel heating, fuel compressors, condensate return pumps, feedwater pumps, and circulating water pumps.

These items are added together, then divided by the total system (high-energy-level output) capacity in mbh. In large systems, the use of increasingly less machinery volume to achieve given amounts of energy conversion or heat transfer tends to higher K_h values.

Because of the many advantages a variable temperature fluid offers, the most popular heating fluid systems are hydronic, requiring a pumping power linearly proportional to the product of the pumping head and the flow rate. The 20 F temperature drop from gravity systems used in product design and pipe sizing tables has been accepted as a norm. However, two significant advantages result from longer system temperature drops: less pumping power is required and smaller pipe sizes are called for.

Specific system thermal power

Specific system thermal power (the Tau functions τ_c and τ_h) is expressed in units of thermal power per ton of refrigeration (MBH/ton) or per unit thermal capacity output (MBH/MBH). The annual thermal energy requirement, though not linearly related to the Tau functions, will, in most cases, vary proportionally. The numerators of these functions are input values, so inefficiencies in thermal conversion systems, convection and radiation losses, and thermal system parasitics must all be considered.

Energy functions

The specific power functions discussed above can be computed quite readily as building system designs are developed and as the machinery and components are selected. Reducing each function will contribute greatly to the minimization of building power use. However, in the field of energy economics, efficient use of available resources is the prime target, and it does not necessarily follow that reducing the electric and thermal power requirements will minimize building energy consumption. The next step, therefore, involves the specific system energy evaluation functions for thermal and electric energy.

The quantitative value of all input energy has been established and reduced to specific units. When the designer begins the process of converting these units into energy functions, he must study such variables as hourly weather profiles, anticipated building use schedules, and the reduced load characteristics of each energy consumer or conversion device.

The initial loads, which resulted in the determination of the Beta and Pi functions, are usually calculated to satisfy performance requirements during anticipated extreme conditions. However, building requirements impose loads which are less than the design load most of the time.

Once the reduced load profile has been established, therefore, the various components and subsystems must be analyzed to determine their respective power consumptions at each reduced load condition. Virtually every energy conversion system has, on its capacity versus input energy curve, a point where the power input per unit of output is minimum: this is, the point of optimum efficiency. Even those subsystems which have relatively low input as a function of output will have an exponential rise with reduced load, except that the rate of increase will be reduced.

The part load profiles are then combined with the reduced thermal and electric load power inputs for the different components. The resulting annual thermal energy is expressed in Btu's divided by the building area, yielding the specific thermal energy consumption, ϵ_t, expressed in MBtu/sq ft. Similarly, the specific annual electric energy consumption, ϵ_e, is expressed in kW-hr/sq ft.

In units of energy, ϵ_e can be combined with ϵ_t by multiplying ϵ_e by the energy constant, C_e, required to generate the power. This constant will vary (depending upon available electric source, generating efficiency, distribution losses, etc.) from 8500 to 17,000 Btu/kW-hr. The product $\epsilon_e C_e$ can then be added to ϵ_t to give the summary specific building energy function, Σ, in MBtu/sq ft. In a sample study of ten similar use buildings in the same geographic area (Chapter 23) this function varied from 193 to 433 MBtu/sq ft.

Conclusion

The conscientious application of the concept of building energy economics will, in most cases, increase the engineering costs associated with building systems design, but should significantly reduce investment costs, power and energy consumption, and, consequently, energy costs.

Yet until an organized system of basic evaluation functions is universally employed, the application of energy economics in building systems will remain totally subjective. If these concepts were to be applied to the energy dynamics of a representative sample of buildings, then a control range of the functions could be made available to the industry.