What Is an Energy-Efficient Building?

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Abstract

Proposed regulations in Brazil call for minimum energy efficiencies in building design and appliance manufacture. These regulations are expected to translate into lower operating costs for the occupants, reduced energy demand for the utilities, and potentially lower carbon emissions for the country. The concept of "energy efficient" buildings has immediate implications on regulations, economics, energy demand, and the environment. A definition is also needed to compare building energy performance or to assess absolute energy efficiency. We propose three criteria for an energy efficient building: 1) the building must be equipped with efficient equipment and materials appropriate for the location and conditions; 2) the building must provide amenities and services appropriate to the building's intended use; and 3) the building must be operated in such a manner as to have a low energy use compared to other, similar buildings. An efficient building must, at a minimum, be above average in all three aspects. When setting minimum efficiency standards, a definition of energy efficiency based on minimum life cycle costs is likely to result in much stricter standards—and greater energy savings—than a strategy based on eliminating the least efficient units.

Introduction

There are examples of "energy efficient" buildings in every major country. Curiously, many of these buildings have high energy consumptions when compared to other efficient buildings, or even when compared to similar, "inefficient" buildings in the same city. Some buildings appeared to be energy efficient in the design stage but evolved into energy-guzzling buildings by the time the building was actually occupied. We have also observed traditionally designed buildings that are claimed to be energy efficient simply by installing a single efficiency device that, at best, can only affect a tiny fraction of the building's total energy use. Designers of other buildings have claimed that their buildings are efficient simply because they meet the minimum efficiency regulations. In this paper, we explore the concept of "energy efficient" and implications that it may have on regulations, economics, energy demand, and the environment. This is not just an academic question because energy regulations, energy rating schemes, shared-savings programs, and utility forecasts are all based on some aspect of energy efficiency. We focus on two aspects: 1) defining an energy efficiency standard for new buildings, and 2) comparing the energy efficiency of different buildings.

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Setting Energy Efficiency Standards

Proposed regulations in Brazil [1] and existing regulations in many other countries [2] call for minimum energy efficiencies in building design and appliance manufacture. These regulations are expected to translate into lower operating costs for the occupants, reduced energy demand for the utilities, and lower carbon emissions for the country and world. Prescriptive standards, that is requiring minimum levels for insulation or efficiency for equipment, have been around for over seventy years, especially in cold regions such as Scandinavia [3]. However, the State of California (USA) [4] was the first government to establish a construction standard based on the building's total energy consumption rather than a combination of specific measures. The foundation of this approach was a maximum energy "budget" for each major building category and in each climate zone. This approach–which was developed over twenty years ago–has been imitated (and improved upon) in dozens of other building codes around the world, including ASHRAE 90.1, and the US Energy Policy Act of 1992 (EPACT) [5].

But what is the correct energy budget for an "efficient" building? There are three general approaches to selecting a maximum budget:

- Negotiated
- Statistical
- Minimum life cycle cost

A negotiated approach means simply selecting a budget with no formula or clear procedure. This approach may be taken when, for example, a standard is developed through discussions between the government and the building industry. In practice, nearly all standards contain an element of negotiation.

The statistical approach seeks to determine the present range of performance. Then a standard is chosen such that only the lowest 50% (or some other number) would meet a new standard. The Europeans used this approach in the initial efficiency regulations for residential refrigerators [2]. The US ENERGY STAR Buildings Program aims to certify only the buildings with a rating above 75% (roughly corresponding to 25% of the buildings) [6]. In Japan, the "TopRunner" appliance efficiency program identifies the best performance presently available and sets the standard so that all new units must surpass that in five years [7].

The life cycle cost approach seeks the efficiency levels that yield the lowest lifetime costs (taking both investment and energy operating costs into account). These calculations begin with a conventionally constructed building or appliance as a baseline, and then examine the trade-offs in initial investments in energy-saving technologies to energy costs. This approach has been adopted in the United States, Australia, and Europe (to some extent).

The impact of these different strategies can be enormous. Unfortunately, it is difficult to demonstrate because buildings are complex devices with hundreds of trade-offs. Instead, we show the impact of three different energy budget strategies applied to a single appliance: refrigerators. Figure 1 shows actual consumption data for "top-freezer" refrigerators sold in the United States in 1989. The approximate levels of the three strategies are shown as lines. These lines slope upwards with increasing volume because this is the primary determinant of energy consumption (at least for refrigerators with the same features).

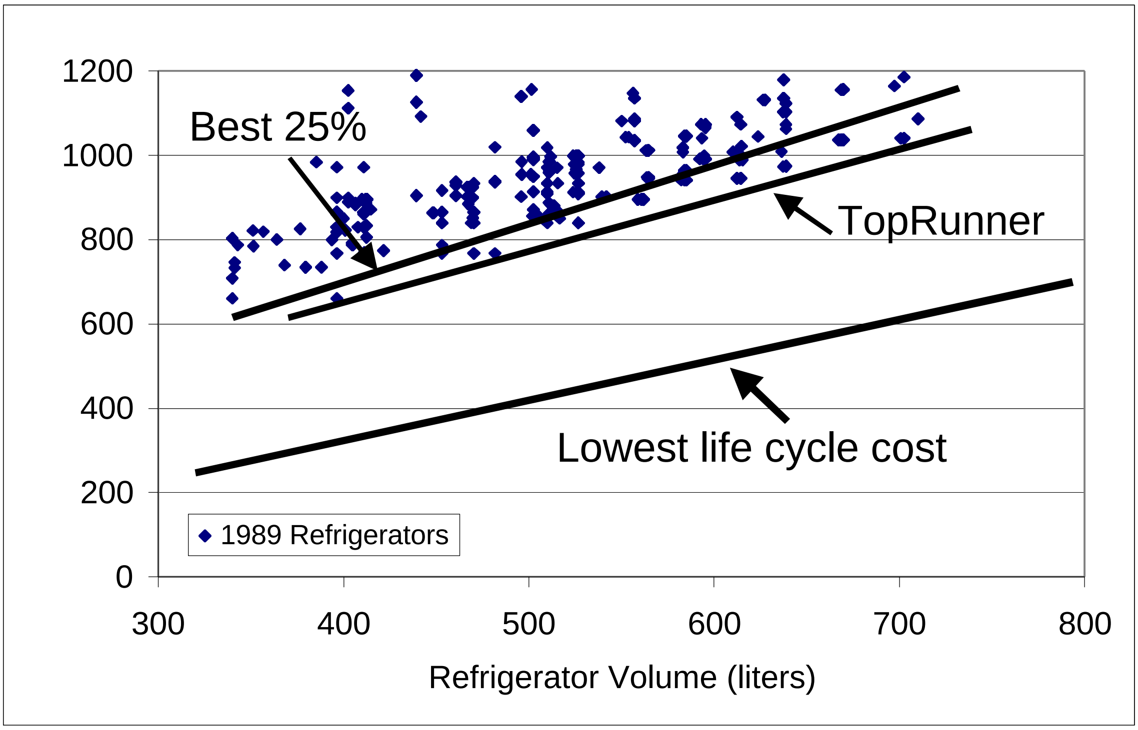

Figure 1. Electricity use of refrigerators manufactured in 1989 with lines showing different standards-setting strategies for future refrigerators.

The "Best 25%" reflects the strategy of selecting a standard that allows 25% of the current models to meet a future regulation. This approach would appear to be an effective means of eliminating many inefficient models and greatly increasing energy efficiency.

The "TopRunner" approach identifies the most efficient units in each category and then requires all units to have lower energy use than that model after five years. This is equivalent to drawing a line connecting the units with the lowest consumption. This strategy will save more energy than the best 25% strategy, possibly a lot more if one manufacturer offers exceptionally efficient units.

The "Lowest life cycle cost" line is calculated from an engineering economic analysis of baseline, 1989, units. In this case, one baseline was a 500 liter refrigerator, consuming roughly 900 kWh/year. Energy efficiency measures were added to the baseline refrigerator until the life cycle costs began to increase. The slope was determined by connecting the energy use for the lowest life cycle costs. Substantial energy savings will result if manufacturers have been selling particularly inefficient models, where inexpensive improvements will yield large savings.

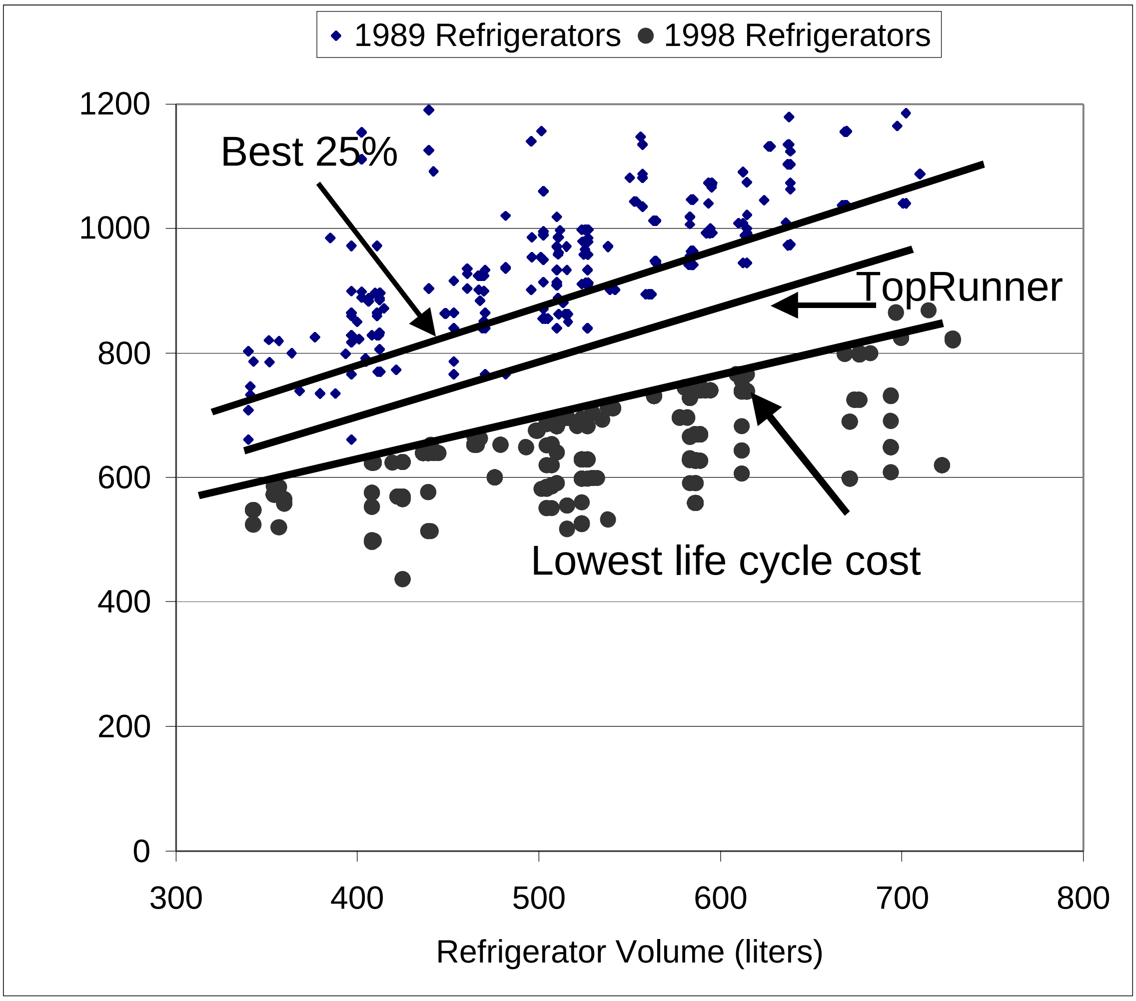

Figure 2. Electricity use of refrigerators manufactured in 1989 and 1998 with lines showing different standards-setting strategies.

Figure 2 demonstrates that, when pressed by a standard, the manufacturers were able to achieve the savings anticipated in the engineering-economic analysis. All of the 1998 refrigerators were able to either meet or surpass the standard. (Curiously, manufacturers often used lower-cost technologies not anticipated by the analysts.). Note that these levels would not have been considered technically feasible if existing models were used as a guide.

This example illustrates how different concepts of efficiency can have enormous impacts on regulations and potential energy savings. There is no single “correct” concept and none of these approaches is “wrong”, but one needs to be aware of the relative impacts of the strategies.

Assessing the Energy Efficiency of a Building

Thanks to computer simulation programs, it is relatively easy to estimate the energy use of a building design. Such models are essential for calculating peak demand and other aspects of complex buildings. A wide range of models exist to perform this kind of calculation. Each model has its own strengths and weaknesses (not to mention errors) [8]. In addition there remain many subjective aspects involved in the translation of a building design into an input file suitable for the simulation program [9], but the general approach is now internationally accepted.

Assessing the building's efficiency is more difficult. In the example with refrigerators, energy efficiency can be easily represented with a single value, that is kWh per year. Buildings are much more complicated because efficiency encompasses many factors. For example, how should energy consumed in the form of electricity be compared to other fuels? Does cooling energy get counted the same as heating? Should peak demand be considered as a factor in energy efficiency? Is the energy running cost the ultimate definition of efficiency?

Even without answering all of these questions, the building's predicted performance can be compared to a building standard or other designs (simulated or actual). Very simple efficiency criteria can be assessed. For example, does the building meet the design goals? Is one design superior to another?

But how does one assess a building's energy efficiency after it has been built and is operating? This question touches on many issues, from simply ensuring proper operation of a single building to broader questions of appropriate energy rating systems, shared savings contracts, and measuring the success of building standards programs [6]. There are two aspects of this question:

1) comparing (or ranking) the energy efficiency of buildings
2) absolute assessment of a building's energy efficiency

In practical terms these translate into two questions. First, how can a person decide if one building is more efficient than another building? Second how can a person decide if a building is "efficient"? Thus, the first requirement is a means of establishing relative efficiency and the second is a means for establishing absolute efficiency. The second aspect is more challenging than the first. Again, there is no single correct result, and reasonable people may differ. In this section we describe some of the problems of finding the best indicator of a building's efficiency.

One way to assess efficiency is to simulate the building's energy use and compare it to a target value. The simulation approach has some value in that it reveals the ideal behavior of a building or its behavior with standardized weather and operating conditions. On the other hand, the simulation approach ignores the wealth of information about actual conditions, such as the utility bills, data from Energy Management Systems (EMS), and known occupancy patterns. More important, a simulation approach cannot even begin to address important aspects of construction, operation, and maintenance. For example, is the building performing as designed? Is something broken? Can the building be improved?

A more attractive approach is to infer efficiency from operating data such as is done in the ENERGY STAR program [6]. For example, a simple performance indicator is a building's total annual energy use divided by its floor area. These values are widely known and are appropriate for comparisons of similar buildings (such as schools in the same city). However, it is easy to confuse a low-energy building with an energy-efficient building (and a high-energy building with an *in*efficient building). A low-energy building is not efficient if the low energy use is achieved by providing reduced amenities, such as lower ventilation rates, uncomfortable inside temperatures, or shorter occupancy schedules. At the other end, a building with a high energy consumption is not necessarily inefficient if it is operating 24 hours per day or contains unusual, energy-intensive, activities.

To illustrate these points, we compiled detailed data on eleven houses in seven countries and calculated twenty different indicators of energy efficiency [10]. A portion of the results are shown in Table 1. In the course of this compilation, we found that international comparisons are complicated by inconsistent definitions of many key terms, some of which are fundamental to all indicators, such as floor area and conversions from site to primary energy.

We investigated the impact of different indicators by observing how the ranking of the houses changed. For example in Table 1, the position of House "D" changes dramatically depending on the choice of indicator. Our major conclusions were:

- The ranking of houses by different indicators is critically dependent on the treatment of electrical energy. Houses that appear very efficient in terms of site energy may fall in apparent efficiency when this consumption is converted to primary energy at 1 kWh = 10MJ of primary energy.

- Space heating energy is declining in importance, and now is less than one third of energy use, even for homes located in very cold climates. At the same time, energy use of appliances is increasing (especially when treated in terms of primary energy). Indicators need to reflect total energy use of buildings rather than focus on space heating.

- Homes with similar physical characteristics and equipment are likely to maintain their relative ranking across a broad range of indicators. Occupants and appliances certainly will affect the absolute values, but the rankings remain the same.

- The quality of the indoor environment, such as temperature, air quality, and other amenities, are not adequately reflected in any of the indicators. Environmental quality rises in importance because some amenities are energy-intensive.

Table 1. Ranking of 11 house in terms of primary energy use

House ID	Space Heat per m2	Space heat per person	Space Heat per HDD18	Space Heat per HDD18 per m2	Total Energy	Total Energy per m2	Total Energy per person	DHW Energy	Lighting and Appliances
B	B	B	I	B	I	B	K	C	K
I	I	I	B	I	B	C	B	D	I
C	C	C	C	F	C	D	I	B	B
E	F	K	F	C	K	I	C	K	H
F	D	F	E	D	H	K	H	J	C
K	E	G	K	J	E	J	A	I	E
G	J	A	H	H	D	F	F	H	D
D	G	E	J	G	J	H	D	F	A
H	K	H	G	E	F	A	G	E	J
J	H	D	A	A	A	E	E	A	F
A	A	J	D	K	G	G	J	G	G

This study was limited to homes in very cold regions, so unique problems associated with comparing cooling performance did not even arise. Assessing cooling energy performance is particularly complex because cooling energy use is a combination of loads caused by differences in temperature and humidity, solar gain, and internal heat sources. The relative contributions also fluctuate through the day and are extremely sensitive the environment around the building. In addition, the size of these loads are difficult to measure and normalize.

These conclusions, while based on examination of only a few houses, also apply to national studies and comparisons. The difficulties in evaluating performance of individual houses have implications for measuring the success of national or regional policies to improve energy efficiency and to reduce CO_2 emissions [11]. If the desired efficiency information is not revealed in a small group of well-documented buildings, then it will surely not be revealed in the same indicator based on cruder, national statistics.

We found a similar situation with commercial buildings [12]. For example, commercial buildings with large data processing centers appear to be very inefficient if one fails to make an allowance for this near-industrial activity occurring within them. Similarly, buildings operated 24 hours/day may appear to be inefficient because they have high energy use. When their energy use is adjusted to reflect these extended schedules, they may rank among the best.

More complex assessment techniques are possible. One approach is to treat the building as a “black box” and derive performance parameters from time series energy, weather, and other data [3]. (This technique is often called “inverse modeling”.) Some of these parameters can be associated with the building’s energy efficiency, even if they do not have direct physical interpretations.

Elements of an Efficient Building

Even if it is impossible to define a single indicator of building energy efficiency, we believe that an energy-efficient building must contain elements from three categories:

- The building must contain energy-efficient technologies that, when operating as designed, will effectively reduce energy use. Put another way, it is impossible for an energy-efficient building to be poorly insulated in a cold climate or have a low COP chiller in a hot climate.
- The building must supply the amenities and features appropriate for that kind of building. Thus, an office must provide around 60 hours/week of suitably conditioned air, lighting, and equipment.
- The building must be operated in such a manner as to be efficient. The evidence of this operation is low energy use relative to other, similar, buildings.

An efficient building may not excel in all three of these aspects, but the building must offset an "average" value in one aspect with "excellent" values in the others. A very clever and attentive operator, for example, might be able to extract low energy use from an only moderately efficient physical plant.

With this kind of definition, it may be possible to establish a kind of "score" or rating system for energy efficiency. The score would be based on the scores for the three separate aspects. In principle, this approach would be flexible enough to recognize different strategies to achieve high energy efficiency. The first requirement, that is, the building must contain equipment and materials that permit it to be efficient, could be based on a simulation or design criteria. The second requirement, that is, the building must have appropriate amenities, could be assessed with an on-site audit. The efficient operating requirement could be judged either against other, similar buildings or against simulations of prototypes calibrated to that building's operating schedule, weather, and other factors.

The energy associated with the construction and demolition of a building plays an increasingly important role as the operating energy declines. Thus, an energy efficient building may need a fourth element: low energy consumption for construction and demolition. This is already important in Japan because buildings are traditionally replaced after only twenty years [13].

The Next Controversy: What Is a Zero Energy Building?

An increasing number of buildings use renewable sources of energy (solar, wind, geothermal) at the building site to provide part or all of its energy needs. Are these buildings efficient, even when they use absurdly large amounts of renewable energy? The answer depends on the objective; they are energy efficient with respect to fossil fuels and CO_2 emissions, but they are probably an overall waste of resources (especially money).

Recently, the concept of "zero energy buildings (ZEB)" has been promoted. On the face of it, the ZEB would appear to mean *a building that relied entirely upon energy captured on site to provide all the desired amenities*. But the United States Department of Energy offered the following definition: "*cost-effective buildings that have zero net annual need for non-renewable energy*" [14]. This definition allows the building to be connected to the electrical grid.

Later, in the face of various political (and practical needs) the DOE revised the definition to: "*Any building that demonstrates significant integration and optimization of both energy efficiency and site power generation*"[15]. It is not clear what this means beyond some good intentions. Designs for a zero energy building meeting these three definitions would be very different in appearance, operation, and cost, not to mention technical feasibility.

Conclusions

We cannot answer the question posed in the title of this paper, "what is an energy efficient building?" But we have shown some of the problems in moving from this simple goal to practical measures. First, we showed how the strategy for creating an efficiency regulation will have an enormous impact on the energy savings. Minimizing the life cycle cost of a building or appliance typically results in much greater savings than by eliminating the units with the worst performance, or even exceeding the performance of the best unit presently available. Buildings are more complicated than appliances because their design involves many more energy trade-offs. For buildings, no single indicator of efficiency is likely to give a fair ranking. Indeed, rankings of efficiency are likely to fluctuate depending on the indicator chosen. There is no single correct indicator of efficiency, but it's important to recognize the bias that may result when using just one.

Even with these limitations, we think that it is still possible to identify some characteristics of an efficient building. We defined three basic criteria for an energy efficient building: 1) the building must be equipped with efficient equipment and materials appropriate for the location and conditions; 2) the building must provide amenities and services appropriate to the building's intended use; and 3) the building must be operated in such a manner as to have a low energy use compared to other, similar, buildings. In the future, the energy embodied in construction and demolition may also need to be considered in judging efficient buildings.

Finally, we raised the special case of defining a zero energy building. Here, small changes in the definition translate into vastly different technical consequences for the design of the building and its relationship to the utility.

Acknowledgments

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