INDICATORS OF ENERGY EFFICIENCY IN COLD-CLIMATE BUILDINGS

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Summary

Indicators of energy efficiency are used as screening tools for energy audits, establishing measures of performance in energy-savings contracts, and tracking improvements in efficiency. The purpose of this project was to develop and test new and existing indicators of a building's energy efficiency. We explored energy indicators from the perspective of building scientists, that is, how does the choice of indicators affect the apparent efficiency of single buildings?

We compiled detailed data on eleven houses in seven countries and calculated twenty different indicators of energy efficiency. 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. 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

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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.

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 reduce CO_2 emissions.

Introduction

The purpose of this project was to develop and test new and existing indicators of a building's energy efficiency. Such indicators have many applications, such as in screening tools for energy audits, establishing measures of performance in energy-savings contracts, and tracking improvements in efficiency. These indicators should make it easier to identify houses that are truly energy efficient and to assist in comparisons with other buildings. We approached the problem by studying individual homes rather than aggregate statistics. Other IEA projects are examining indicators from an aggregate perspective. This project did not achieve all of its goals, but the analysis of individual homes provides insights and recommendations for compilation and analysis of aggregate or national data.

We explored energy indicators from the perspective of a building scientist. How does the choice of indicators affect the apparent efficiency of specific homes? And since indicators are used to compare performance, does a home's *ranking* change with the indicator? Most important, do the rankings make sense? Here again, we wanted to use our building science background to ensure that the indicators and rankings make physical sense. These questions are best answered through examination of individual houses rather than with aggregations (that is, collections of houses) because detailed characteristics are generally not collected for large groups of houses. Nevertheless, an indicator that fails to accurately rank efficiencies of individual homes is unlikely to succeed when comparing the entire housing stocks of countries.

Technical Approach

Data Collection

The first step in this project involved finding homes suitable for the project. These homes needed to be well-documented with both building characteristics and energy consumption data. Furthermore, we wanted the homes to be located in cold climates, that is, where space heating energy dominated. We hoped to acquire the following information about each building:

- One year of energy consumption data
- Submetered space heat
- Floor area
- Weather
- Number of occupants
- Basic construction and equipment characteristics

We collected data from over 250 energy-efficient houses and apartment buildings located in ten different countries.

Unfortunately, we encountered several problems with this approach. First, few buildings had a complete data set (discussed in detail below) and, second, nearly every data set required extensive recalculations in order to get it into a consistent format. Homes that were carefully monitored and investigated typically lacked whole-year data or were not occupied in a conventional way. (In other words, they were "research" houses.) Homes with a complete year of energy consumption data typically lacked important information about the building's construction characteristics or submetered energy data. (In other words, these were "normal" houses.)

Our first workshop (in Lund, Sweden) addressed these problems and developed a different strategy. We decided to focus on a few, well-documented houses. Since the reports or documentation rarely provided all the information needed, we also wanted a building scientist to "sponsor" each home. Most of the participants were familiar with the homes from their country. In many cases, they had been involved in the associated research project.

In addition, we expanded the compilation to include both typical and high-efficiency houses. A more diverse collection was likely to give more insights.

In spite of the "sponsor" approach, obtaining sufficient data for the homes proved to be more difficult than anticipated. Some of the problems were:

- Number of occupants was not recorded
- Lack of whole-year energy consumption data
- Failure to monitor (or report) whole-building energy use
- Lack of submetered energy consumption
- No information on amenities or levels of service (such as indoor temperatures)
- Inability to estimate home's overall heat loss coefficient (k-value)

The participants were sometimes asked to try to obtain more data for this project. This was achieved with some (but not complete) success.

Description of the Investigated Houses

We made compromises in order to create a diverse collection of homes and to speed up the project. As a result, some of the homes do not meet all our collection criteria. The results are still valid, but we were unable to explore as many indicators as we had initially planned. Eleven homes were finally selected for the intense examination. Those homes are shown in Table 1.

Table 1. Key to the homes

Letter	Country	City, State/Province
A	Finland	Espoo
B	Japan	Sendai, Miyagi
C	Germany	Schrecksbach, Hessen
D	USA	Moscow, Idaho
E	USA	Hanover Park, Illinois
F	USA	Missoula, Montana
G	USA	Missoula, Montana
H	USA	Eagle River, Alaska
I	Sweden	Malmo
J	Canada	Edmonton, Alberta
K	Poland	Poznan

In this report, we refer to a house by the city in which it was located or by its letter. Some features of each house are presented in Table 2. Energy data were also compiled and summarized in Table 3**.**

These homes represented a wide range of locations, designs, and efficiencies. Floor areas ranged from 107 to 223 m^2. Five houses were all-electric, one house was connected to a district heating system, and the remaining five burned fossil fuels for space and water heating. Two nearly identical homes–those in Missoula–were selected to show the impact when several variables were the same. A description of each house is available on the web site.[2]

Table 2. Summary of the houses' characteristics

House ID	Floor Area (m^2)	Year Built	Space Heating	Fireplace	Heat Pump	Water Heating
A	164	1991	Elec.			Elec.
B	165	1987	Oil			Oil
C	168	1987	Oil			Oil
D	325	1989	Elec.		yes	Elec.
E	112	1993	Gas	yes		Gas
F	223	1994	Elec.		yes	Elec.
G	162	1994	Elec.		yes	Elec.
H	163	1994	Elec.		yes	Elec.
I	109	1982	Elec.			Elec.
J	215	1990	Gas			Gas
K	107	1980	Dist. heat			Gas

[2] Please access the web site through Alan Meier's home page: www.LBL.gov/~akmeier .

Table 3. Summary of energy data (annual site energy)

House ID	Total Energy Use (kWh)	Space Heating (kWh)	Water Heating (kWh)	Appliances & Lighting (kWh)
A	24,108	9,020	6,232	8,856
B	11,894	3,839	4,425	3,630
C	16,414	9,610	1,512	5,292
D	18,200	8,125	1,300	8,775
E	38,101	13,774	14,829	9,498
F	21,855	4,450	3,724	13,681
G	29,595	6,580	6,570	16,445
H	16,696	8,391	3,294	5,011
I	10,300	2,200	4,200	3,900
J	45,820	27,547	7,403	10,870
K	19,653	13,244	4,472	1,937

Insights Gained During the Acquisition of Data

In spite of widespread monitoring activity, there were surprisingly few buildings with sufficient data for inclusion in the database. Still fewer projects collected enough data to permit their home's performance to be compared with others. Many buildings were incompletely monitored. For example, many houses had carefully instrumented solar heater systems or ground source heat pumps but lacked whole-house energy metering. Other projects monitored energy use for only a few months, while still others were unclear regarding conversion of site energy to source energy, building thermal characteristics, or the status of the occupants. In short, it was harder than expected to assemble a group of comparable buildings. There are, of course, exceptions to these findings. For example, the NRCan databases of R2000 homes have all of these data (and more). But the NRCan database is truly an exception. A modest amount of international coordination and a subsequent compilation effort could easily remedy this problem.

International comparisons are complicated by inconsistent definitions of many key terms. Expressing the information in completely consistent terms proved to be impossible. These inconsistencies undermined the accuracy of the absolute comparisons. In the end, the absence of clear and consistent definitions of basic physical characteristics–even surprisingly simple characteristics– became a major finding of this project. Four examples of inconsistent terms that could introduce significant errors are:

- Livable floor area calculation
- Calculation of heating degree-days
- Energy content of fuels
- Conversion of electrical energy into primary energy

We explain each of these inconsistencies below and describe the impact that they may have on our analyses. Several of them are characteristics that appear as the "denominator" in normalizations of energy use. As such, building characteristics are just as important energy consumption data.

Livable Floor Area Calculation

The floor area is a key normalization factor, so it is important to avoid the introduction of recurrent errors or bias. One example of a bias is in the definition of the floor areas for attics. The living area under the roofs (or attics) represents a significant fraction of the total floor area in many European houses. Unfortunately, every country calculates the livable portion under the sloped attic differently (see Figure 1 below).

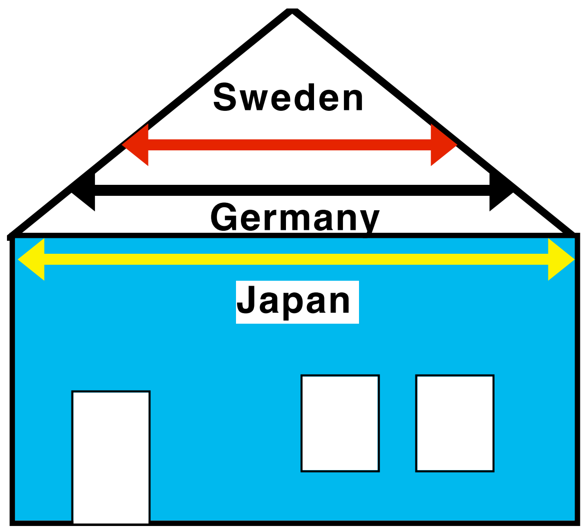

Figure 1. Different definitions of attic floor area

As Figure 1. shows, the same house in these three countries would report substantially different floor areas. The differences for a typical house are shown in Table 4.

Table 4. Theoretical impact of different definitions of attic floor area

	Japan	Germany	Sweden
Minimum height in attic to be considered livable area (m)	0	1.5	1.9
Reduction in calculated attic floor area when attic is 6 m wide.	0%	37%	47%
Reduction in total house floor area when house is 6 m wide and has a ground floor and an attic.	0%	18%	24%

If this inconsistency is overlooked, then Swedish houses will appear 25% less efficient (per unit of floor area) than their Japanese counterparts. Adjusting for this discrepancy alone will make Swedish houses appear much more efficient.

Other inconsistencies in the floor area definition arose in the course of comparing results. These include use of gross versus net floor area, treatment of basements, garages, and distinctions between heated floor area and total floor area. These definitions are typically inconsistent between countries and sometimes even inside countries because they vary with construction type.

Calculation of heating degree-days

The number of degree-days can still be a useful indicator of the severity of the winter. However, there is no single definition of a degree-day; indeed, each country appears to have special variants to suit its needs. We found significant variation in definitions of degree-days, as shown in Table 5 below.

Table 5. Definitions of degree-days

Country	Heating begins when	Inside temperature assumption	Calculation	Start/Stop
Germany, Poland	Tout < 15 and	20	Tin - Tout	Sept - May
Sweden, Finland, Norway				depends on location
autumn	Tout <12	20	17 - Tout	
spring	Tout<10	20	17 - Tout	
United States	Tout < 18	21	18-Tout	
Japan	Tout< 18	n/a	18-Tout	depends on location

We conclude that there is no simple conversion of degree-days collected with one procedure to those collected with another procedure. We did not estimate the potential differences in estimates due to this problem, but recommend that a standard procedure for calculating heating degree-days or other indicator of the severity of the winter be established. No indicator will be entirely satisfactory; for example, how should availability of sunshine be treated? (This is a key factor for passive solar homes.) Developing a consistent indicator could be a task of an international standards-making organization, such as ISO, or the IEA. This task is becoming simpler because weather tapes are becoming increasingly available. Almost any indicator can be generated from these tapes.

Energy Content of Fuels

Europe and the United States measure the energy content of fuels differently. When oil (or natural gas) is burned, one of the products is water vapor. About 8% of the fuel's total heat is used to evaporate the water. If the combustion products are condensed, then this 8% can be recovered. European countries generally use the "low" heating value for fuels, that is, the heat obtained from combustion without recovery of the latent energy in the water vapor. The United States and Canada use the high value. Thus, energy data based on fossil fuel consumption will be inconsistent. The difference is 8%. After adjusting for the 8% difference, houses in the United States and Canada will gain in efficiency relative to European houses.

To further confuse the situation, German LPG distributors have begun to advertise the "high" heating values for their fuel. This move lowered the apparent cost per GJ of LPG vis-à-vis competing fuels.

Conversion of electrical energy into primary energy

Many research reports fail to adequately distinguish between primary and site energy consumption data. The confusion is mostly confined to electricity consumption. Many researchers convert all energy consumption directly in kilowatt-hours. This leads to two kinds of ambiguities:

- is the energy consumption electricity or another fuel?
- if the original energy was electricity, was it converted to primary energy equivalent? And if yes, what conversion rate was used?

These are problems of inconsistent reporting rather than with technologies or energy efficiency. Still, they prohibit easy comparisons or, worse, suggest that one technology is superior when in fact it is not.

A second, related, problem of the appropriate conversion factors of site to primary energy also arose. The Schrecksbach house was an example of ambiguity in reporting. This house burned oil for space heat, but the report listed all values in kWh. In some cases, oil and electrical energy were combined, but no conversion factor was given. Since the factor can raise energy contribution of electricity as much as three-fold, a consistent approach is essential for valid comparisons. We converted electricity at the rate, 1 kWh_{elec} = 10MJ of primary energy, although this rate was not accepted by all of the participants. In Norway, for example, essentially all electricity is generated from hydroelectric facilities, so the conversion rate is unrealistic.

One way to assess the impact of uncertainty in site/primary energy is by inspection of Table 6, Table 7, Table 8, and Table 9 for total energy use. The lowest house remains the lowest energy consumer but little else is the same. Not only does the ranking change, but so does the distribution.

Indicators of Efficiency

We calculated twenty different indicators of energy efficiency based on the data from the eleven homes. These indicators are listed below.

- Total energy
- Area-normalized total energy

- Occupant-normalized total energy
- Space heat
- Area-normalized space heat
- Occupant-normalized space heat
- Climate-adjusted space heat
- Climate- and area-adjusted space heat
- Appliance and lighting energy per person
- Domestic hot water energy per person

Area adjustment means "divided by floor area", occupant normalized means "divided by the number of occupants", and climate-adjusted means "divided by degree-days". All ten of the above indicators were calculated for both site and primary energy (hence twenty different indicators). These calculations are summarized for site energy in Table 6 and Table 7. The results are converted to primary energy in Table 8 and Table 9. (These tables include three columns from Table 3.)

We were unable to develop as many indicators as we hoped, because we lacked a complete data set. We particularly regretted the absence of consistent and complete information describing each building's thermal characteristics (k-value), equipment characteristics (such as heating system efficiency), and indoor temperature settings. Detailed climate adjustments were also impossible because outside temperature data were inconsistent, both in the definitions and the location of data collection.

Table 6. Total and space heating indicators expressed in terms of site energy (kWh)

House ID	Space Heat	Space Heat per m2	Space Heat per person	Space Heat per HDD	Space Heat per HDD per m2	Total Energy per m2	Total Energy per person
A	9,020	55	1,804	1.7	10.4	147	4,822
B	3,839	23.3	960	1.53	9.3	72.1	2,974
C	9,610	57.2	2,403	2.8	16.7	97.7	4,104
D	8,125	25	2,708	2.16	6.6	56	6,067
E	13,774	123.5	6,887	3.61	32.3	256.5	14,302
F	4,450	20	1,113	1.03	4.6	98	5,464
G	6,580	40.6	1,645	1.52	9.4	182.7	7,399
H	8,391	51.5	2,098	1.43	8.8	102.4	4,174
I	2,200	20	730	0.68	6.2	95	3,430
J	27,547	128	13,774	4.93	22.9	162.4	17,475
K	13,244	123.8	2,207	3.28	30.6	165.6	2,953

Table 7. Appliance, lighting, and domestic hot water indicators expressed in terms of site energy (kWh)

House ID	Appliances and Lighting	Appliances and Lighting per person	Appliances and Lighting per m2	Domestic Hot Water	Domestic Hot Water per person	Domestic Hot Water per m2
A	8,856	1,771	54	6,232	1,246	38
B	3,630	908	22	4,425	1,106	26.8
C	5,292	1,323	31.5	1,512	378	9
D	8,775	2,925	27	1,300	433	4
E	9,498	4,749	85.2	14,829	7,415	133
F	13,681	3,420	61.4	3,724	931	16.7
G	16,445	4,111	101.5	6,570	1,643	40.6
H	5,011	1,253	30.7	3,294	824	20.2
I	3,900	1,300	36	4,200	1,400	39
J	10,870	5,435	50.5	7,403	3,701	34.4
K	1,937	323	18.1	4,472	745	41.8

Table 8. Total and space heating indicators expressed in terms of primary energy (kWh)

House ID	Space Heat	Space Heat per m2	Space Heat per person	Space Heat per HDD	Space Heat per HDD per m2	Total Energy per m2	Total Energy per person
A	30,067	183.3	6,013	5.67	34.6	490	16,072
B	4,413	26.7	1,103	1.76	10.6	130.8	5,400
C	11,046	65.8	2,761	3.22	19.2	181.1	7,606
D	27,083	83.3	9,028	7.19	22.1	186.6	20,222
E	13,774	123.5	6,887	3.61	32.3	512.1	28,549
F	14,833	66.5	3,708	3.43	15.4	326.7	18,212
G	21,933	135.4	5,483	5.07	31.3	609	24,662
H	27,970	171.6	6,993	4.76	29.2	341.4	13,913
I	4,490	41	1,500	1.39	12.7	193	7,010
J	28,117	130.6	14,059	5.03	23.4	316.5	34,065
K	16,659	155.7	2,777	4.12	38.5	286.5	5,110

Table 9. Appliance, lighting, and domestic hot water indicators expressed in terms of primary energy (kWh)

House ID	Appliances and Lighting	Appliances and Lighting per person	Appliances and Lighting per m2	Domestic Hot Water	Domestic Hot Water per person	Domestic Hot Water per m2
A	29,520	5,904	180	20,773	4.155	126.7
B	12,100	3,025	73.3	5,086	1,272	30.8
C	17,640	4,410	105	1,738	434	10.3
D	29,250	9,750	90	4,333	1,444	13.3
E	28,494	14,247	255.6	14,829	7,415	133
F	45,603	11,401	204.5	12,413	3,103	55.7
G	54,817	13,704	338.4	21,900	5,475	135.2
H	16,703	4,176	102.5	10,980	2,745	67.4
I	7,960	2,650	73	8,570	2,860	79
J	32,610	16,305	151.5	7,403	3,701	34.4
K	6,679	1,113	62.4	7,319	1,220	68.4

There are many different ways to present the results. In this study, we are most interested in how the *ranking* of the houses changes with different indicators. We considered numerous graphical displays to facilitate interpretation. Each display had its own merits and but none proved to be generally superior. Below we present three different approaches. The first display, Table 10 for site energy and Table 11 for primary energy, show the ranking (or order) of the eleven homes. House D (Moscow, USA) has been shaded to aid in tracing one house's changes in the rankings. This format allows compact presentation of the rankings but does not show the quantitative differences.

Table 10. Ranking of homes in terms of site energy

House ID	Space Heat per m2	Space Heat per person	Space Heat per HDD	Space Heat per HDD per m2	Total Energy	Total Energy per m2	Total Energy per person	DHW Energy	Lighting and Applianc es
I	F	I	I	F	I	D	K	D	K
B	I	B	F	I	B	B	B	C	B
F	B	F	H	D	C	I	I	H	I
G	D	G	G	H	H	C	C	F	H
D	G	A	B	B	D	F	H	I	C
H	H	H	A	G	K	H	A	B	D
A	A	K	D	A	F	A	F	K	A
C	C	C	C	C	A	J	D	A	E
K	E	D	K	J	G	K	G	G	J
E	K	E	E	K	E	G	E	J	F
J	J	J	J	E	J	E	J	E	G

Table 11. Ranking of homes in terms of primary energy

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

The second approach (Figure 2), a histogram, displays the approximate values and the distribution of values (but requires much more space).

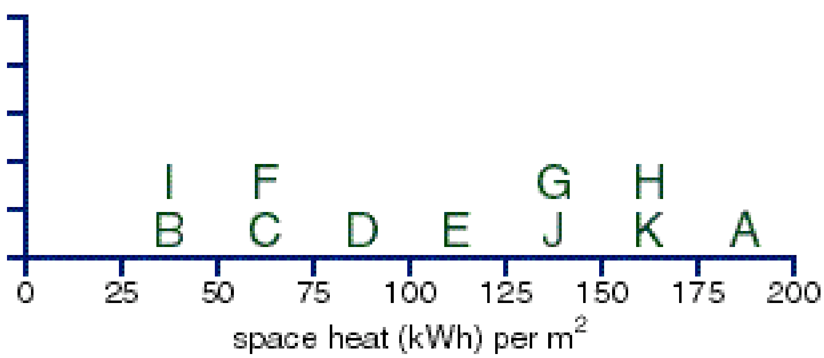

Figure 2. Histogram display of one indicator (where vertical axis represents the number of homes in that bin)

A third approach (shown in Figure 3 and Figure 4) combines the table approach with a graphic so as to give rough indications of actual values as well as ranking. This approach is used below in the detailed discussion in the Discussion of the Indicators. The drawback of this approach is that the figures cannot be easily generated; they require several steps and two software applications.

Discussion of the Indicators

These results allowed us to trace the impact of the choice of indicator on the ranking of the houses. Four detailed discussions on the following topics are presented:

- Performance ranking of specific houses
- Implications of site vs. primary energy
- Impact of extreme situations (e.g. occupancy, plug loads, climate)
- Declining significance of space heating indicators

These discussions also draw upon additional information presented in the original documents or from the project participants.

Performance Ranking of Specific Houses

Figure 3 and Figure 4 show the rankings for the indicators considered. This format, however, also shows rough numerical rankings in addition to the simple, ordinal ranks shown in earlier figures. By tracing the behavior of selected houses, one can see the impact of the changes.

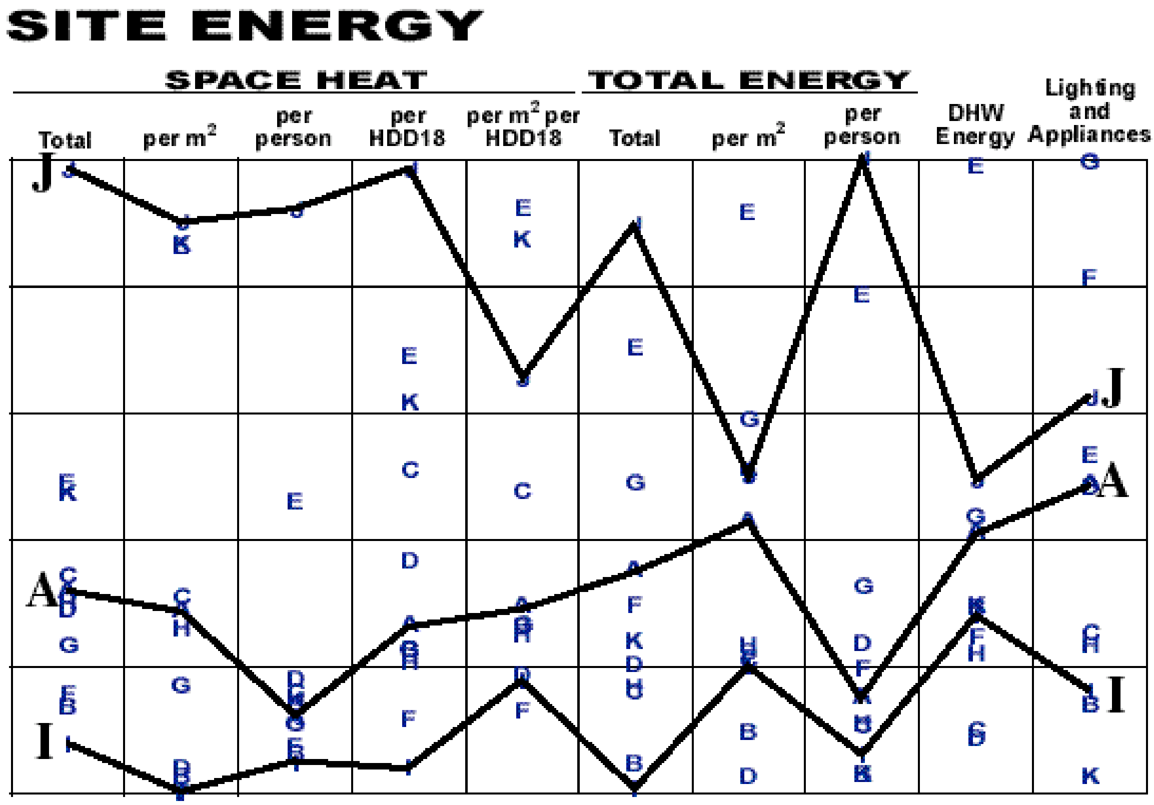

Figure 3. Indicators expressed in terms of site energy

House J (located in Edmonton, Canada) had the highest site energy use in the group. This is no surprise because it was not built to be particularly energy efficient and was located in a cold climate. It had the highest total energy consumption and space heating energy consumption. It remained the highest user of space heat until adjustments were made for both floor area and climate (but still remained among the highest). It also had high appliance energy use (surpassed only by the two Montana houses).

There remains uncertainty about the Edmonton house's total floor area and how the 2-car garage and basement was counted. It is possible that floor area was overstated by about 30% which, if the indicators were calculated with a smaller floor area, would make the Edmonton house the highest user in virtually all rankings.

The Edmonton house's apparent efficiency changes dramatically when viewed in terms of primary energy, because it used natural gas for space and water heating. (Recall that site electrical energy was converted to primary energy at the arbitrary rate of 1 kWh = 10 MJ.) It was still among the less efficient houses but no longer the worst. The largest shift in ranking occurred in water heating, where the Edmonton house became the fourth lowest user. These precise re-orderings must be treated with caution, because a slightly different site-to-primary conversion factor would lead to a different ranking.

House A (located near Espoo, Finland) was designed to consume half as much heating energy as similar small, one-story Finnish houses. The goal was achieved; the house consumed only 9,000 kWh for space heating compared to 19,000 - 21,000 kWh for similar Finnish houses, even though the house's five occupants maintained the living area between 20°C and 22°C in the winter. In addition, the house had a mechanical ventilation system with heat recovery.

The indicators (based on site energy) support the conclusion that the house was reasonably efficient. Other houses used less energy, but the occupants of the Espoo house probably enjoyed higher inside temperatures and air quality. Lighting and appliance energy was high because the occupants installed many outside lights and used a sauna.

Again, the situation changed dramatically when the indicators were expressed in terms of primary energy. Instead of appearing to be reasonably efficient, the Espoo house then ranked among the least efficient.

The Malmo house (House I) used the least total energy, both in site and primary energy. The Malmo house was situated in the very south of Sweden. It was a two-story house with a wooden framework. It was constructed in 1982 and its energy use was monitored for two years. Two adults and one child occupied the house. The house was generally unoccupied during the day, but there were no significant vacations during the monitoring period. The mean outdoor and indoor temperature during the heating season was 3.5°C and 23°C, respectively.

A glassed-in veranda was attached to the south side of the house and served as a kind of solar heater. In this veranda the ventilation inlet air was preheated 5° before it entered the house. This measure energy saved roughly 1000 kWh/year. The mechanical air change rate in the dwelling was 0.7 air changes/h. The house had electric resistance radiators to provide space heat combined with the "preheated" inlet air. The domestic hot water was heated with the exhaust air and an electric heat pump.

The foundation was a slab on ground with 100 mm of mineral wool below the concrete. The U-value was 0.24 W/m2°K. The external walls had 240 mm of mineral wool between light studs. The U-value of the external walls were 0.17 W/m2°K. The roof had 350 mm of mineral wool which corresponded to a U-value of 0.11 W/m2°K. The windows were triple-glazed with gas filling.

The Malmo house's high efficiency was reflected in nearly all the indicators. Several factors may have contributed to the house's high efficiency, including heavy insulation, a semi-active solar heating system, heat recovery systems, and relatively low occupancy. The house's low energy use was achieved without causing discomfort to the occupants; at 23°C, the average inside temperature was even higher than that maintained in the Espoo house.

Several technologies in the Malmo house failed after a few years. The heat recovery devices were abandoned and the exhaust air heat pump water heater was removed. The solar heating system was also disconnected. (Unfortunately, subsequent-year energy consumption data were not available.) While durability was not an explicit topic of this project, it clearly needs to be addressed in the design, construction, and operation of energy-efficient houses.

Implications of Site vs. Primary Energy

Conversion of site electricity to primary energy greatly changes the ranking. However, the extent of the re-ordering depends entirely on the choice of conversion factor of electricity into primary energy. (In this report, we used 1 kWh = 10 MJ, that is about a 30% conversion efficiency.) Since five houses in our study were electrically heated, there was substantial re-ordering after adjustment for primary energy.

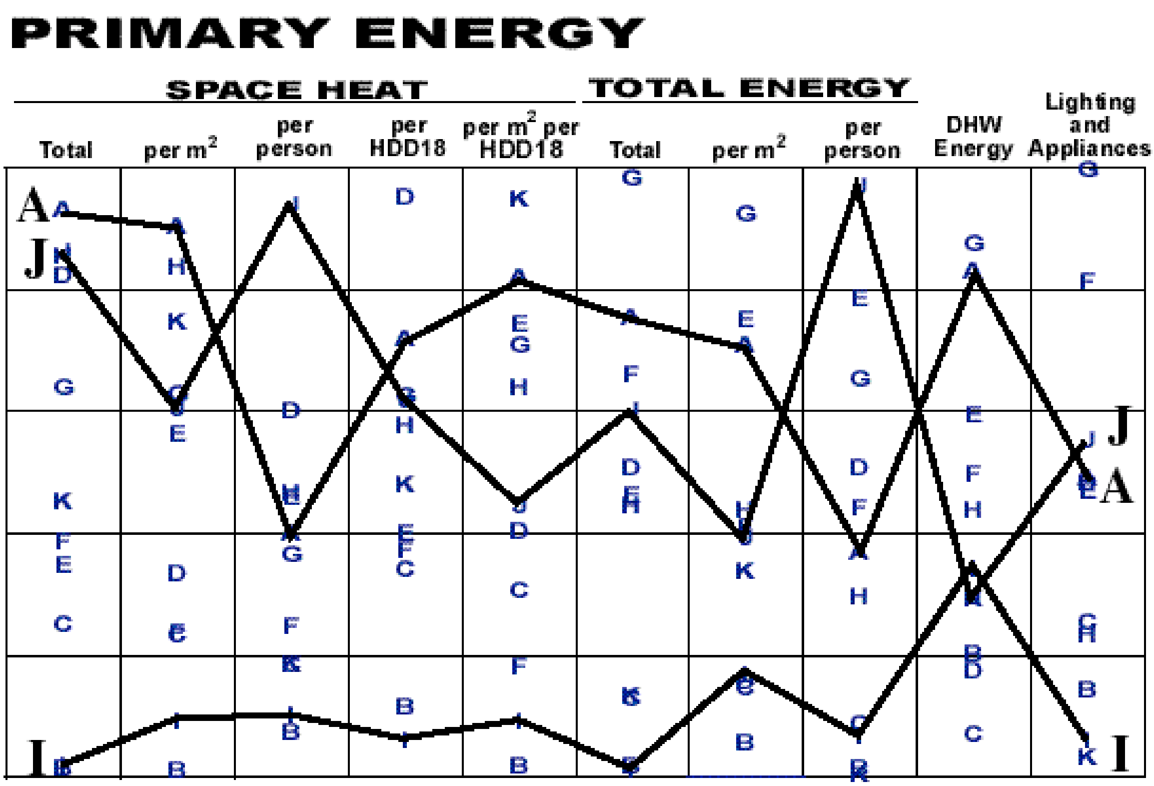

Figure 4. Indicators expressed in terms of primary energy

The Hanover Park house (House E) burned natural gas for space heat and DHW. In terms of site energy, it ranked among the least efficient. However, when its energy consumption was expressed in primary terms, the Hanover Park house's efficiency rose into the middle of the range. The same kind of re-ordering occurred for the Edmonton house.

Impact of Extreme Situations

We now describe the impacts on ranking of three unique situations: high occupancy combined with low appliance energy, low indoor temperatures, and similar construction combined with identical climate. It is useful to trace their impacts on the indicators because they demonstrate the robustness–and the vulnerability–of the indicators to deviations from common situations.

The Poznan house (House K) deviated from the other houses in three significant ways: it was small (107 m2), had many occupants (six), and consumed very little electricity for appliances. In addition, it was the only house whose space heating and DHW was provided through a district heating system. The Poznan house could be mistaken for a moderately efficient house when in fact the low energy use was achieved through fewer amenities and services and, to a lesser extent, the primary energy conversion rate for district heat energy consumption. This conclusion could not have been made without additional information about the building's thermal characteristics and appliances.

The Sendai house (House B) demonstrates the impact of extreme low indoor temperatures on the performance indicators. Its total energy was the second lowest and appeared to be very efficient (based on the indicators). The actual situation was very different. The four occupants maintained the house at 13 - 20° during the winter, but most of the time above 17°. A special electrical heater (a "kotatsu") provided personal heating for the occupants when sitting in the living room which allowed them to maintain comfort at lower room airtemperatures. The heat exchanger was used only during the daytime. Cold water was normally used in the washing machine. The house's thermal characteristics (and size) were not much different from the Edmonton house (House J). The Sendai house was indeed a low energy house and reasonably efficient, but the low energy was to a great extent a result of lower services and amenities compared to other, comparable houses.

The two Missoula houses (Houses F and G) were built by the same builder and were located only a few hundred meters from each other. Their construction and energy features, such as levels of insulation, windows, and heating system were nearly identical. The two houses also had the same climate. The two major differences in the two Missoula houses were the floor areas and occupant behavior. House G also used a little more energy for appliances and lighting. The impact of these differences affected the houses' energy performance in a remarkably consistent manner. House G's indicators were consistently higher than House H's. If the Missoula houses are a guide, then homes with similar physical characteristics and equipment are likely to maintain their relative ranking, while the difference in energy use can be explained by differences in occupant behavior, floor area, appliance energy, and climate.

Declining Significance of Space Heating Energy in a House's Total Energy Balance

Climate normalization (that is, dividing the space heat energy by degree-days) in the eleven houses had almost no effect on the ranking. In fact, normalizing for both degree-days and floor area resulted in no significant change in ordering. These houses were located in heating-dominated regions and had relatively similar floor areas, so these houses don't reflect the true diversity of international conditions. Nevertheless, more complex indicators did not appear to provide any greater insights than simple ones.

Indicators of space heating have become less relevant as indicators of a house's general efficiency for two reasons. First, space heating energy use in most houses was generally less than a third of total energy use (even for those homes in very cold climates). The energy use of appliances and water heating must be taken into consideration. And, because appliance waste heat may provide a major portion of heating requirements, the energy consumed by the traditional heating system can no longer be examined in isolation. For example, the sauna in the Espoo house consumed nearly 6 kWh/day. Most of this eventually became useful internal gains. Should Finnish houses (or the indicators that reflect their energy performance) be penalized for such uses?

Second, the energy used for space heating in cold-climate homes and warmer-climate homes is nearly the same; the difference is that cold-climate homes employ increasingly sophisticated technologies to achieve low energy use. Put another way, the greatest distinction between new, cold-climate houses and warmer-climate houses is not the amount of space heat consumed–they are about the same–but the technologies employed to achieve the same level of thermal comfort. Simple indicators of energy performance cannot capture these effects. For these reasons, total energy use is increasingly the most appropriate indicator of performance.

Conclusions and Recommendations

Indicators of energy efficiency are prescriptions for condensing a large amount of information into a simple number (or numbers) to facilitate evaluation or comparison. Indicators serve many different functions. For a single house, an indicator can be used as a simple way to track its performance over time or evaluate the success of a retrofit. At a regional or national level, indicators can be used to observe the impact of energy efficiency policies on a large collection of houses.

There is no reason to expect that a single indicator will work in all cases, but it is useful to understand which indicator will be most appropriate and the data that need to be collected to support it. This project investigated the strengths and weaknesses of different indicators of energy efficiency by examining the way in which the choice of indicator affected the rankings of buildings. By understanding the implications at a single-house level, one can better interpret observed changes at the macro level.

Our major conclusions are as follows:

- Uncertainties and inconsistencies in definitions of non-energy data (the "denominator data"), such as floor area and definitions of degree-days, introduce large uncertainties in the indicators that are often larger than the uncertainties in energy data. These definitional problems undermine the value of international comparisons, especially because they introduce biases rather than random error.

- 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. This rises in importance because some amenities are energy-intensive.

In this project, we sought to understand the implications of using specific indicators on large, poorly-defined groups of houses by examining the impact on a small group of well-defined homes. This approach emphasized the building science aspects of the indicators rather than the statistical aspects of large data sets. This approach was not as successful as hoped because of the complexity of attempting to develop a standard measure. Nevertheless, this project demonstrated some of the fundamental problems with indicators at both practical and physical levels.