ture from coral to fleshy algal domination on the high island of Martinique is described by W. Adey, P. Adey, R. Burke, L. Kaufman, *Atoll Res. Bull. No. 218* (1977).
44. The term coral bank is used here to distinguish the early phase of a bank barrier reef from that of the "classical" framework reef. I consider this a critical distinction, because the large-scale morphology of the bank base is influenced primarily by shelf currents, whereas that of the early framework reef is initially influenced largely by antecedent topography.
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50. The "Atlantic" sea level curve is a mean of the following published curves: C. Neumann, Bermuda (*18*); A. C. Redfield, Louisiana [*Science* **157**, 687 (1967)]; D. W. Scholl, F. C. Craighead, Sr., M. Stuiver, Florida [*ibid.* **163**, 562 (1969); W. Newman *et al.*, eustatic curve based on east coast North American data [*Congres INQUA* **8**, 795 (1971)]; Curray *et al.*, Pacific Mexico after I. Macintyre and P. Glynn (*25*); and J. Milliman, Atlantic U.S., also after (*25*). The "Pacific" curve is a mean of the following: F. Baltzer, New Caledonia [*C.R. Acad. Sci.* **271**, 2251 (1970)]; J. Schofield, Gilbert and Ellice Islands, New Zealand [*J. Geol. Geophys.* **20**, 3 (1977)]; R. Pickrill, New Zealand [*N.Z. Geogr.* **32**, 17 (1976)]; B. Thom and J. Chappell, Australia [*Search* **6**, 90 (1975)]; C. Lalou *et al.*, Tuamotos (*32*); J. Tracey and H. Ladd, Enewetak (*31*). Most of these curves have been collected together by A. Bloom, *Atlas of Sea-Level Curves* (International Geological Correlation Program, Project 61, Ithaca, N.Y., 1977). The extension of the curves into the future presumes a symmetrical Holocene rise and fall of the sea level around the present. This would be an apparent maximum length for the Holocene interglacial, since at that length it would be somewhat longer than the interglacial 125,000 years ago.
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56. The sea level curve is after N. Morner [*Can. J. Earth Sci.* **8**, 132 (1971)], with maxima and minima based on Barbados [R. P. Steinen, R. Harrison, R. Matthews, *Geol. Soc. Am. Bull.* **84**, 63 (1973)]; the position of the peak at 29,000 years ago is based on studies in progress, St. Croix [Macintyre *et al.*]. It is not the intention of this diagram to fix precisely the shelf margin buildup at the localities cited. Although some sea level positions are becoming better established (and these are most critical to the discussion) others are only guesses, for example, the position of sea level below 50 m and especially that of the "miniglacials." The diagram is intended to show the type of processes that must have been operating to control reef and carbonate shelf development in tropical seas. Understanding of the details of late Pleistocene climate and sea level was greatly enhanced by the study of the Barbados reef cap. However, it seems very unlikely that the present growth of *A. palmata* on Barbados is climate-limited as suggested by K. Mesolella *et al.* [*J. Geol.* **77**, 250 (1969)]. There is a strong possibility that the submerged ridge along the west and southwest of the island, as yet undrilled, is an early Holocene *A. palmata* reef, perhaps overlying another formed 30,000 to 40,000 years ago. These factors, together with the differing elevations attached to concurrent date sets, and the possibility of an irregular rate of uplift suggest the likelihood of a greater complexity of events than considered by the Barbados workers. A reevaluation in the light of newer data on Caribbean reef development would probably improve our insight into Pleistocene sea level events.
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Energy and Labor in the Construction Sector

Bruce Hannon, Richard G. Stein, B. Z. Segal, Diane Serber

Efforts to evaluate the potential for energy conservation in the construction industry have usually focused on reducing operational energy consumption, with little concern for the energy cost of the construction activity itself (*1*). A study of energy use in both building and nonbuilding construction indicates that construction activity accounts for a significant amount of national energy consumption (*2*). Knowledge of how energy is used in the construction process and of energy expenditures during construction that reduce operational energy consumption could contribute significantly to programs designed to diminish the nation's overall energy demand.

In our study we considered the employment generated by the construction industry as well as the labor impacts of various energy-saving construction options. We also investigated the possible inverse relation between total energy and labor requirements for construction (*3*).

The basis for the study was an energy and employment input-output model of the construction industry (*2, 4–7*). The model describes energy flows through the U.S. economy in 1967. The data for 1967 are the most recent available through the Bureau of Economic Analysis in regard to completeness and comprehensiveness. Although there have been some changes in the kinds and extent of construction activity as well as some changes in manufacturing and construction methods, the general information is still applicable.

The power and versatility of the model come from two sources. First, the model is comprehensive. It includes nearly 400 sectors, 49 of them in the construction industry (Fig. 1), and covers the entire U.S. economy. Second, the model makes it possible to determine the total direct and indirect energy requirements, as well as the labor requirements of various industrial activities (*8*).

Direct inputs to an activity are those actually consumed by the industrial sector engaged in the activity. For example, the refined petroleum needed to operate construction equipment represents direct energy use. Indirect inputs to an activity, on the other hand, represent consumption (or employment) in sectors not engaged in the given activity but which supply inputs to it via the chain of production.

For example, the use of a steel beam in construction represents an indirect use

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0036-8075/78/1124-0837$02.00/0

of both energy and labor. The energy embodied in the beam includes the energy used directly by the steel manufacturer, as well as that required for the mining and extraction of raw materials, production and transportation of intermediate goods, maintenance of factories and offices, plus all other activities related in some way to production of the steel beam. The indirect labor related to the beam includes an allocation of employment in all of the industries that contributed to the production of the beam. (Double counting of indirect requirements is avoided.)

The concept of total energy is important in examining the construction industry. Of the total U.S. energy requirement in 1967, construction activity accounted for slightly more than 10 percent (*9*), of which less than a quarter was direct. Over three-quarters was indirect energy, embodied in nonenergy inputs such as building materials.

Our investigation also showed that the employment generated by construction activity accounted for more than 12 percent of the total U.S. full-time labor equivalents in 1967. Just under half of this total was for direct labor.

Summary. An energy input-output model was used to investigate energy and employment in the construction industry. The model covered nearly 400 industrial sectors and was used to determine the impact of construction activities on total national energy consumption in 1967 and to study the patterns of total energy use and employment within various construction categories. For the construction of new buildings, total energy consumption could be reduced by 20 percent by selecting less energy-intensive building materials and assemblies for fixed programmatic requirements, by expending energy in construction to minimize the total lifetime energy cost of buildings, and by energy conservation in industries that supply direct and indirect inputs to the construction sector of the economy.

Energy Conservation in Building Construction

Our analysis focused on the more than 6 percent of total national energy consumption (nearly 58 percent of total construction energy use) committed to the construction and maintenance of buildings. In buildings, such design components as walls, windows, and roofs affect operational performance through their thermal, light, and air transfer characteristics. The trade-offs between energy used for construction and operational energy requirement are important.

Three approaches to energy conservation in the construction of new buildings were considered.

Selecting less energy-intensive materials and components. We determined the total (direct and indirect) energy costs per unit for a number of typical building materials, including wood, concrete, brick, and steel products. Using this information, we investigated alternative building assemblies with similar performance characteristics. We discovered wide variations in the energy embodied in interchangeable units. This analysis can be expanded to examine the energy required for alternative methods of constructing an entire building.

Analyzing lifetime energy costs. The lifetime energy costs are the total of the capital energy costs for initial construction, plus the operating energy costs through the life of the building, plus the additional capital energy cost for the maintenance or replacement of components during the life of the building. For convenience, the "lifetime" of a building is assumed to be the typical mortgage period for that type of building. In reality, the actual building lifetime is often longer. We compared life-cycle requirements for different thermal performances for alternative wall assemblies and for entire building shells.

Reducing energy consumption in the production of building materials and assemblies. These materials may be sold directly to construction contractors or to intermediate industries. Such products may, in turn, pass through a number of stages before they are used in new buildings (*10*).

Energy and Employment Modeling

Using the energy and employment model developed by the Energy Research Group at the University of Illinois (*4, 11*), we calculated 1967 energy and labor intensities for aggregate construction categories (Table 1). For each category, we determined the total (direct and indirect) intensities for five energy types: coal, crude petroleum, refined petroleum, electricity, and natural gas. The total primary energy intensity was calculated from the energy intensity of coal, crude petroleum (which includes natural gas), and the hydro and nuclear power portions of the electricity intensity. This is a nonredundant measure of the energy which moves from the earth into the production of goods and services.

New building construction in 1967 required 62,000 British thermal units (*12*) of total primary energy for every dollar of activity—with 12.6 percent of that for direct, on-site energy. New nonbuilding construction required 98,000 Btu's per dollar of activity, of which nearly 32 percent was for on-site use. On the whole, new construction required 32 percent more total primary energy per dollar than maintenance and repair activities in 1967. The breakdown by type of energy shows the strong dependence of construction activities on petroleum and petroleum-based products.

Table 1 indicates an inverse relation between the effects of energy use and employment in 1967. The less energy-intensive new building construction category generated about 9.2 direct and indirect full-time equivalents (FTE) per $100,000 of activity. The more energy-intensive new nonbuilding construction activity generated about 8.8 total FTE per $100,000. This inverse relation also appeared to hold for new compared to maintenance activities in general. The last column of Table 1 displays the percentage of each category's total labor requirements representing direct (on-site) labor.

Although these percentages are higher than their energy counterparts, indirect labor requirements play an important role in the total employment generated by construction activities.

Table 2 shows some of the more detailed information from the energy and employment input-output model. In the table, construction sectors are ranked by decreasing total primary energy intensity. Total energy requirements for 1967 are shown alongside the intensities. Although petroleum pipelines and gas utilities required the most energy per dollar of construction activity, highways and single-family homes consumed the most energy in 1967 because of the high volume of such activities.

Combining the 1967 dollar costs per square foot for various building types (*13, 14*) with the total primary energy intensities of corresponding sectors permitted us to determine the energy costs of building sectors on a square-foot basis (Table 2, last column).

Energy Profiles of Construction Sectors

The methods of energy reduction in building construction can best be determined when there is detailed knowledge available about the total energy cost (direct and indirect) of a particular building type. In our study the total energy cost profiles of the 49 different construction sectors were determined, as well as the composite of all new building sectors (*15*). In building construction, the largest contributor to total energy cost is direct on-site energy—accounting for over 15 percent, mostly in refined petroleum (14.54 percent) (Fig. 2). A further breakdown of the direct energy use of refined petroleum reveals that asphalt, used for paving and roofing, is the largest component (accounting for 59 percent of the direct energy, or 9 percent of the total energy) used in new building construction (Fig. 2) (*16*). In this case the energy is not burned but remains latent in the material. Direct energy use together with ready-mix concrete (8.82 percent), structural steel (5.7 percent), and bricks (3.09

Table 1. Energy and labor intensities for aggregate construction categories, 1967. Energy intensities are broken down by each type of energy. Percentages accounted for by direct (on-site) energy and direct (on-site) employment are given for total primary energy and total labor intensities, respectively.

Construction category	Total output* ($ billion)	Energy intensities (Btu/$)							Total labor intensity	
		Coal	Crude petroleum	Refined petroleum	Electricity	Natural gas	Total primary†	Percentage on-site	FTE per $100,000‡	Percentage on-site
New construction	79.9	19,100	52,700	30,800	3,700	20,700	74,100	20.6	9.07	41.2
Building	54.6	17,500	42,900	21,900	3,700	20,000	62,700	12.6	9.20	39.2
Nonbuilding	25.3	22,700	73,800	49,900	3,800	22,300	98,800	31.7	8.78	45.8
Maintenance and repair Construction	23.4	12,100	42,500	26,900	2,600	14,600	56,200	20.0	9.15	60.2

*From (*34*). †Formed by combining the coal and crude petroleum intensity with the hydro and nuclear portion of the electricity intensity for each construction category [see (*3*)]. ‡Measured in full time equivalents (FTE) per $100,000 of output [from (*5*)].

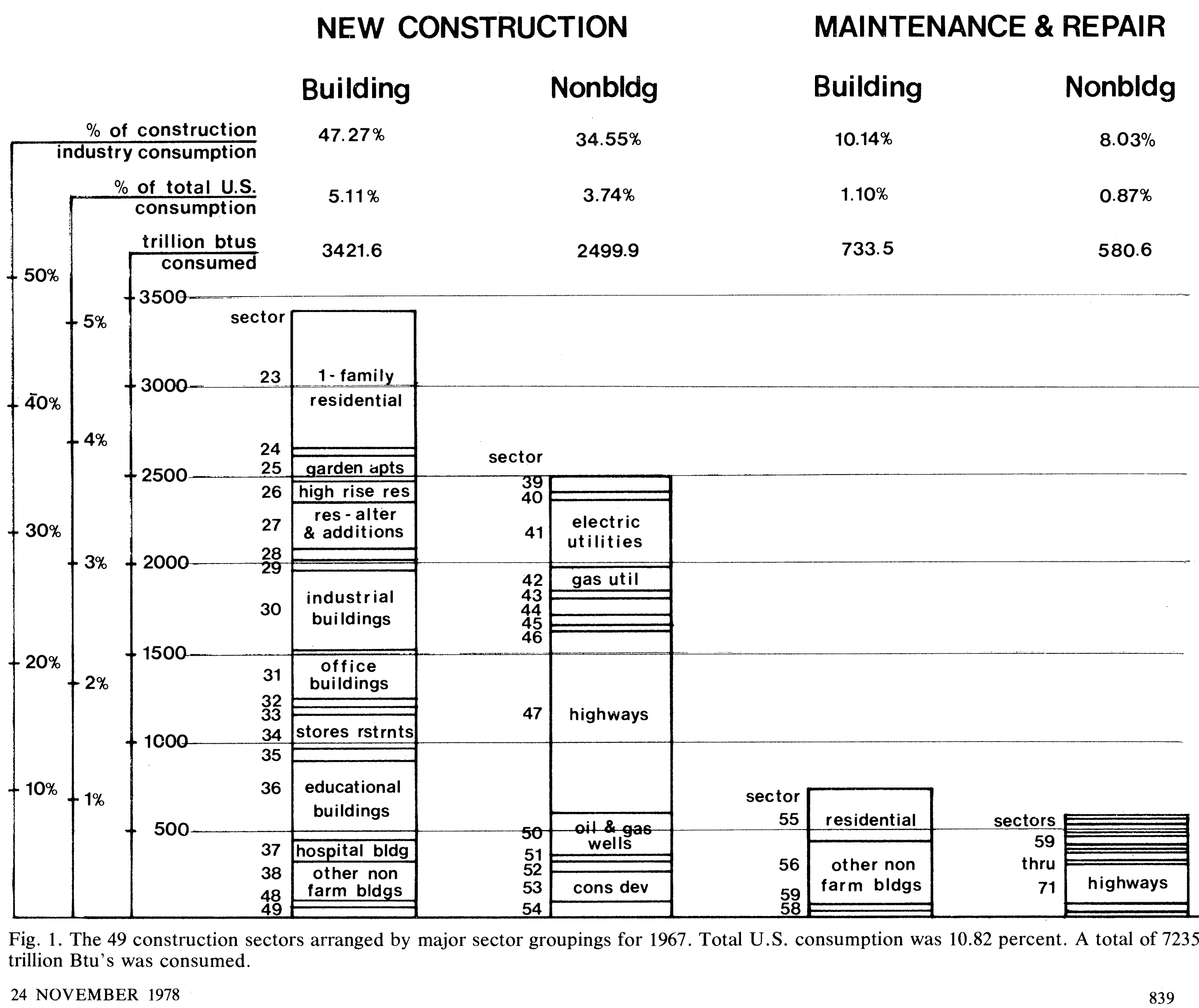


Fig. 1. The 49 construction sectors arranged by major sector groupings for 1967. Total U.S. consumption was 10.82 percent. A total of 7235.6 trillion Btu's was consumed.

percent) represented almost one-third of the entire energy utilization for 1967 in building construction (*17*) (see Fig. 2).

If one examines the contributors to total energy cost related to each building type, two things become apparent. First, there is a large number of small contributors. Second, each building type is different. This means that reducing energy use in the construction industry will depend on many simultaneous decisions, no one of which may seem to be crucial; also, that each building type will have specific opportunities for energy conservation. For example, wood is used extensively in the smaller residential categories, but proportionately much less in most other building types. Structural steel and ready-mix concrete are used extensively in high-rise buildings, although structural steel is used less in residential than in high-rise office buildings. Some typical energy profiles are shown in Fig. 3.

Even greater differences exist between the characteristic profiles for building and nonbuilding construction, both in the direct energy used in nonbuilding construction and in the distribution of embodied energy among the sectors selling to the construction sector under study.

For 1967, the average direct energy used in nonbuilding construction averaged 31.71 percent, varying from 13.22 percent in railroad construction to 84.5 percent in construction for oil and gas exploration. The categories representing 70 percent of the energy used in building construction accounted for only 60 percent in nonbuilding construction.

Table 2. Construction industry sectors and 1967 results ranked by total primary energy intensities. The sectors are from the detailed breakdown used by the Bureau of Economic Analysis, U.S. Department of Commerce. Energy intensity was computed with our expanded energy input-output model, and represents total primary energy required per dollar of activity. The total energy requirement was computed from the expanded model as the sum of the total energy embodied in each direct input to sector. The grand total was 7240 trillion Btu's, or 10.8 percent of the U.S. energy requirement in 1967. The result for labor was 9,382,500 total FTE's generated or 12.8 percent of the total U.S. FTE's in 1967 (*5*, *6*). Figures in parentheses are the percentage of total energy use in each sector which was direct. The total energy per square foot was computed from the expanded model and construction cost figures from (*13*, *14*).

Sector	Energy intensity (Btu/$)	Total energy requirement (trillion Btu)	Total energy per square foot (Btu/ft²)
New petroleum pipelines*	147,200	45.9 (34.2)	
New gas utility facilities	140,000	216.9 (28.6)	
New highways	123,700	1035.9 (39.6)	
Maintenance petroleum pipelines†	117,200	7.6 (36.5)	
New oil and gas wells	116,900	235.6 (30.6)	
Maintenance oil and gas wells	109,100	46.5 (25.5)	
Maintenance farm service facilities	96,300	38.2 (4.8)	
Maintenance conservation and development facilities	93,000	18.0 (73.2)	
New oil and gas exploration	92,900	22.3 (70.3)	
Other new nonbuilding facilities	89,500	82.8 (33.1)	
New conservation and development facilities	84,800	180.1 (50.7)	
Maintenance gas utility facilities	83,100	21.5 (27.1)	
New military facilities	77,800	54.1 (19.2)	
New railroads	77,600	25.4 (11.0)	
New warehouses‡	77,600	57.8 (11.3)	560,000
New sewer facilities	76,800	81.3 (19.6)	
New garages and service stations‡	76,200	32.2 (16.1)	770,000
Maintenance highways	76,000	227.2 (43.6)	
New farm service facilities‡	76,000	57.9 (4.6)	150,000
New water supply facilities	73,700	93.7 (17.1)	
New stores and restaurants‡	73,200	197.0 (18.9)	940,000
Maintenance farm residential	71,300	25.3 (7.4)	
New industrial buildings‡	70,900	463.4 (8.2)	970,000
New dormitories‡	70,600	57.8 (18.5)	1,430,000
Other new nonfarm buildings‡	69,900	231.1 (17.5)	1,450,000
New hotels and motels‡	69,200	69.1 (17.6)	1,230,000
New office buildings‡	68,700	258.7 (17.8)	1,640,000
New education buildings‡	67,900	437.4 (15.5)	1,390,000
New electric utility facilities	66,600	303.9 (12.7)	
New telephone and telegraph facilities*	66,600	109.2 (11.3)	
New religious buildings‡	65,600	68.6 (16.4)	1,260,000
New local transit facilities	62,400	12.7 (17.6)	
Maintenance military facilities†	62,400	52.9 (28.1)	
Maintenance other nonbuildings	62,000	41.1 (50.1)	
Maintenance water supply facilities	61,900	61.5 (23.4)	
New hospital buildings‡	60,600	117.2 (16.6)	1,720,000
New high-rise apartments‡	60,000	118.0 (16.6)	740,000
New single-family housing‡	55,500	781.0 (9.9)	700,000
New farm residential buildings‡	53,800	30.2 (4.4)	560,000
New garden apartments‡	52,900	147.8 (14.5)	650,000
New two- to four-family housing‡	52,100	34.8 (13.4)	630,000
New residential alterations and additions‡	51,600	261.9 (2.9)	
Maintenance residential	50,100	313.7 (7.3)	
Maintenance other nonfarm buildings	49,700	356.3 (10.5)	
Maintenance local transit facilities	48,500	2.1 (20.0)	
Maintenance sewer facilities	45,000	18.1 (22.5)	
Maintenance railroads	42,800	46.8 (12.5)	
Maintenance telephone and telegraph facilities	35,500	18.4 (16.1)	
Maintenance electric utility facilities	26,400	19.0 (12.6)	

*"New" stands for new construction of. †"Maintenance" stands for maintenance construction for. ‡Included in our "new building aggregate" category.

Conservation Through Substituting Materials

All materials used in building construction contain embodied (indirect) energy. Thus, one way of reducing the total energy cost of building would be to substitute less energy-intensive materials, or assemblies of materials, for more intensive ones while maintaining the same final performance criteria.

We applied total energy intensities from our model to refined economic data from the U.S. Department of Commerce (*18*) in order to develop the energy cost for most of the major building materials (*19*) described in units commonly used in the building construction industry (board feet of lumber, square feet of glass, cubic yards of concrete, and so on).

Table 3 gives the total energy costs of some of the major materials and components which contributed to the embodiment of energy for building construction of 1967. The energy cost for materials is shown both before and after delivery to the jobsite. Possible uses for these unit energy embodiments include: estimating energy use for building assemblies or for entire buildings; determining the comparative energy requirements for assemblies or materials with similar performance characteristics; making life-cycle comparisons when insulation is added or other changes are made to the thermal performance characteristics of building assemblies; and examining transportation of materials to the jobsite as a contribution to the embodied energy in buildings.

Energy Cost of Comparative Building Sections

The energy costs for basic materials indicate that an informed choice in selecting building materials could appreciably reduce the energy embodiment in building construction. We carried our investigation a step further by comparing the energy embodied in interchangeable assemblies that would satisfy similar performance criteria. As an example, two structural floor-bay systems were compared.

We compared steel and reinforced-concrete floor systems for an area measuring 900 square feet. Each system, designed for structural economy and typical of contemporary practice in fireproof, high-rise office building construction, uses both steel and concrete in varying proportions. Adding all the embodied energy in all of the materials to the on-site energy use, we found that the 900 square feet of reinforced-concrete construction requires less than 60 percent of the energy needed for comparable steel construction: 154.8 million Btu's versus 263.5 million Btu's (Fig. 4).

The decisive factor is the high energy embodiment in steel. Even in concrete construction, steel represents 55 percent of the total energy embodied. The steel used in concrete structures is all in reinforcing bars, which have a lower energy embodiment per pound than fabricated structural steel: 15,664 Btu's versus 22,698 Btu's per pound.

Similar differences in energy requirements carry through in comparing concrete and steel columns. Thus, the structural frame for a concrete, fireproof, high-rise building will require, in toto, only 60 percent of the energy needed for a steel system meeting comparable design specifications. Including the columns, the difference is about 125,000 Btu's per square foot, or 5/6 gallon of oil, as a national average. (The structural computations for this comparison were based on the New York City Building Code) (*20*).

We then extended our examination of the two floor slabs to include the amount of labor required by each in terms of man-hours (see Fig. 4). Indirect labor was computed by applying labor intensities in terms of man-years per dollar of product (*6*) to prices (*18*) for each component of the two systems, then multiplying the total man-years for all components by the average number of hours worked in 1967 in the general manufacturing sectors (*21*). The figures for the labor needed to transfer the materials from the manufacturer or supplier to the jobsite were derived in a similar manner. Lacking 1967 data on jobsite labor requirements, we established a figure based on 1976 practices and used that (*22*). Few changes have occurred in construction methods in the decade since 1967.

As Table 4 shows, the steel system generated slightly more total employment per square foot than the reinforced-concrete system, but the steel system required far less on-site labor. Bidding experience suggests no decisive cost advantage for one system over the other (*23*). If energy embodiment were the primary decision criterion, however, concrete would be the system of choice.

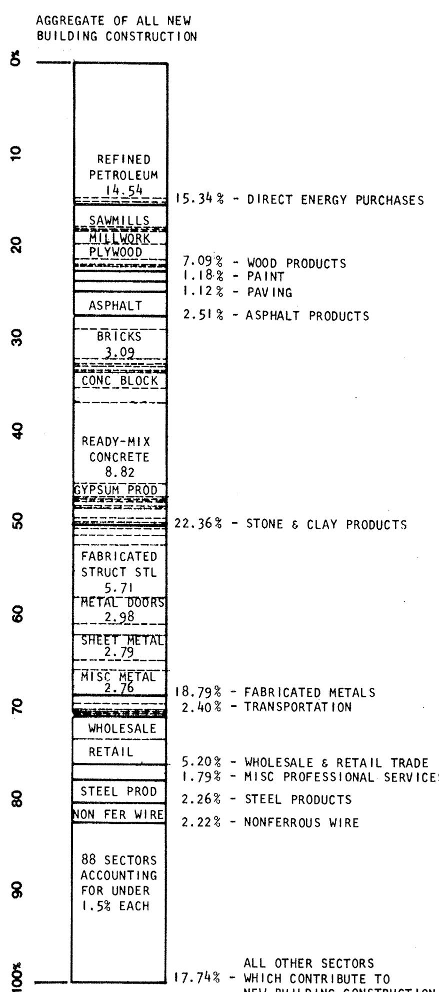


Fig. 2. Allocation of total energy requirements of all new building construction among direct purchases of goods and services (1967).

Conservation Through Energy Life-Cycle Analysis

The lifetime energy performance of buildings is affected by construction decisions. We therefore extended the study to an analysis of the total energy cost (direct and indirect) to cover the lifetime of buildings, accounting for construction energy, operational energy required through the life of the building for thermal losses, and the additional energy inputs needed for maintenance and component replacement.

We tested the assumption that substituting slightly more energy in the initial construction for significantly less operating energy would achieve overall energy savings through the lifetime of the structure, by comparing brick veneer and wood frame walls of several thicknesses. Construction, maintenance, and lifetime operational energy costs for typical wall sections were tabulated.

Figure 5 shows the lifetime energy cost (construction plus operation, maintenance, and so on) for a square foot of various wall assemblies in New York City (based on an average figure of 4848 heating degree-days per year) for more than 30 years of operation. The initial energy embodiment of each assembly is given at zero years of operation (the vertical axis). As time progresses (the horizontal axis), the assemblies induce different operational energy costs based on their ability to resist heat flow (U-factors) (*24*). We have included a factor for maintenance—repainting of shingles every 5 years and replacing some of the shingles at 20 years.

The lines in Fig. 5 cross when the cumulative total energy consumed by each corresponding wall assembly is equal. The brick-veneered wall with 3½ inches (8.75 cm) of insulation requires much less operational energy than the shingled alternative with no insulation. Yet because of the high energy intensity embodied in the brick, approximately 5 years would be required for the brick-veneer wall to register lower energy consumption than the one with shingles, if one counts construction plus operational energy requirements.

There were 844,000 one-family residential housing starts in 1967 (*25*). An increase in insulation, as shown in Fig. 5, would result in a substantial cumulative effect. If one assumes 1280 square feet of exterior wall per building, a total of 1.08 billion square feet of walls were constructed in 1967. The total annual energy saving represented by adding 10 inches (25 cm) of insulation to these surfaces, if one assumes that the national average for heating degree-days per year is 4734 (*26, 27*), would have been 7.73 trillion Btu's. The total energy cost of this option (represented by the total primary energy required for the extra insulation) would have been about 653 billion Btu's per year spread over 20 years. The annual net savings realized through this alternative would have been 7.08 trillion Btu's. In other words, a simple structural modification of all new housing constructed in 1967 could have saved the nation annually the equivalent of 1.1 million barrels of No. 6 fuel oil. Also, the initial energy cost of the added insulation (13.1 trillion Btu's) would have been "paid back" in less than two heating seasons (at 7.08 trillion Btu's per season).

We extended the analysis to the outer shells of two typical houses of 1500 square feet each in the New York City area—one with 3.5 inches of insulation in the walls, 5.5 inches in the roof, and with single-glazed windows; the other with 5.5 inches of insulation in the walls, 11.5 inches in the roof, and double-glazed windows (Fig. 6).

The first has an embodied energy value of about 172 million Btu's. The operational energy demand would be 60.5 million Btu's per year for heat loss by conduction through the building shell. The second has an embodied energy value of 188 million Btu's (9.3 percent more than the other example) and an operational energy demand, due to conduction heat loss, of 35.2 million Btu's per year (42 percent less than the first example). In addition, either building would require 41.8 million Btu's per year to counteract the heat lost through infiltration and the opening of doors and windows. The total energy demanded for heating, therefore, would be 102.3 million Btu's per year compared to some 77 million Btu's per year for the two buildings, respectively (*7*).

Thus, an extra energy embodiment of approximately 17 million Btu's would net a saving of over 25 million Btu's annually. The energy "payback time" for that saving would be less than one heating season. The 25 million Btu's would be directly equivalent to about 4 barrels of No. 6 fuel oil saved per year. Considering the 844,000 private one-family housing starts recorded for 1967 (*24*), the potential annual savings inherent in a relatively simple set of structural adjustments applied to 1 year's new housing would amount to 3.6 million barrels, that is, 1 percent of the 1976 refinery output of No. 6 fuel oil (*28*).

One can minimize the total lifetime energy cost of a building by adding insulation to the optimum thickness on an energy-embodiment basis, and the energy saved by addition of a small increment of insulation can be compared to the energy cost of providing that increment. When the incremental energy savings equals the incremental cost, the optimum thickness from an energy standpoint has been reached. A similar procedure is used to calculate the economic optimum. If present dollar costs for energy and material are used, the optimum thickness would be much thinner than the energy-optimum thickness. Thus, we are faced with a dilemma: Is it better to insulate at today's economic optimum or to the ultimate energy optimum? The answer depends on how fast the relative price of energy will rise and how much one can discount the importance of higher-priced energy in the future.

Table 3. Energy embodiment per unit of material, 1967. All embodiments were derived by multiplying the average dollars per unit (*17*) by the average number of British thermal units embodied per dollar of product (*3*). Special market considerations can affect embodiments. We

Material	Unit	Embodied energy (Btu/unit)	
		Before delivery to jobsite	After delivery to jobsite
Wood products			
Softwood			
Rough lumber	Board foot	5,229	7,661
Dressed lumber	Board foot	5,399	7,859
Hardwood			
Rough lumber	Board foot	6,744	9,816*
Dressed lumber	Board foot	6,633	9,655*
Wood shingles and shakes	Square foot	4,682	7,315
Wood window units			
Double hung	Each	845,671	1,127,234†
Awning and casement	Each	893,021	1,190,349†
Other	Each	1,373,150	1,830,335†
Wood doors			
Panel type, interior and exterior	Each	654,851	872,881†
Flush type, hollow core	Each	259,952	346,502†
Flush type, solid core	Each	893,696	1,191,182†
Veneer and plywood			
Hardwood	Square foot	12,942	17,025‡
Softwood, interior	Square foot	3,790	4,986‡
Softwood, exterior	Square foot	4,393	5,779‡
Prefabricated structural wood members			
Glued and laminated	Board foot	14,673	16,733
Paper products			
Construction paper	Pound	8,841	10,479§
Paint products			
Exterior oil paints and enamels	Gallon	413,066	488,528‖
Exterior water base paints	Gallon	413,519	489,063‖
Interior oil base paints	Gallon	429,932	508,475‖
Interior water base paints	Gallon	369,519	437,025‖
Asphalt products			
Roofing asphalt	Pound	6,701	6,914
Roll roofing, smooth surface	Square foot	7,514	7,753
Roll roofing, mineral surface	Square foot	10,673	11,012
Standard strip shingles	Square foot	24,553	25,334
Asphalt-saturated felts	Pound	13,210	13,630
Tar-saturated felts	Pound	16,416	16,938
Glass products			
Window glass, single strength	Square foot	11,895	13,659
Window glass, double strength	Square foot	13,437	15,430
Plate glass, average (3/16 inch)	Square foot	41,828	48,031
Laminated plate, average	Square foot	185,058	212,504
Stone and clay products			
Portland cement	Barrel	1,526,498	1,582,126
Brick (2 1/4 by 3 5/8 by 7 5/8 inches)			
Common and face	Each	13,570	14,283
Other unglazed	Each	24,306	25,582
Facing tile and ceramic			
Glazed brick	Each	31,749	33,416
Quarry tile	Square foot	46,589	51,031
Ceramic mosaic tile, glazed	Square foot	62,682	68,660
Ceramic mosaic tile, unglazed	Square foot	58,081	63,619

In a study prepared for New York State, we analyzed two government office buildings in Albany for the purpose of reducing their operational requirements (*29*). The buildings were designed in the mid-1960's. They have a combined gross area of 1.2 million square feet, and require 28 million kilowatt-hours of electricity and 626,000 gallons of No. 6 oil annually. At 11,400 Btu's per kWh (the delivered cost in British thermal units of 1 kWh in Albany) (*29*) and 150,000 Btu's per gallon of oil, the annual operating figure becomes 413 billion Btu's or 344,000 Btu's (at the source) per square foot.

In 1967 (a comparable construction year for the two Albany buildings), according to Table 2, the energy embodied in office-building construction averaged 1.64 million Btu's per square foot, or five times the energy needed for 1 year of operation. As we become more energy conscious, however, this ratio can be expected to change.

When the Albany study was initiated, New York State had been operating the buildings in accordance with its own conservation program, mainly involving selective removal of lamps. The result was a 12 percent reduction in total energy consumption. As a consequence of our study, further conservation measures —including the removal of more lamps and the adjustment and rebalancing of the heating, ventilating, and air-conditioning systems in the building—created a projected reduction of about 50 percent in the annual operating energy, to about 149,600 Btu's per square foot. Since no material was to be added, the embodied energy would remain the same; thus, the energy embodied in the buildings would equal the operating energy required to run the buildings for nearly 10 years (*30*).

The recent Government Services Administration standard for new federal-government office buildings (*31*) sets 55,000 Btu's per square foot per year as the maximum on-site energy with which to operate all services in such buildings. The two existing Albany office buildings could comply with this standard by replacing the existing 120,000 square feet of single-glazed glass with double-glazed window glass. At 48,000 Btu's per square foot for the additional 120,000 square feet of glass, this would add 5.8 billion Btu's (or 4800 Btu's per square foot) to the energy embodied in the buildings. The annual on-site energy demand to operate both buildings would be an estimated 60.7 billion Btu's, or slightly over 50,000 Btu's per square foot—the equivalent of 174 billion Btu's at the source or 145,000 Btu's per square foot, which about equals the energy required for 11 years of operation. While the energy cost of the change would be recaptured in 4 months, the dollar cost would not be recovered for 23.5 years. It was the economic factor that caused the decision not to proceed with this option.

Energy Conservation in Key Supply Industries

The approaches to energy conservation described thus far involve reducing direct and indirect energy use by changing construction materials and activities. Another approach would be to apply conservation practices to industries that supply goods and services for construction projects, both directly and indirectly.

We are using the energy input-output

have noted where such impacts were deemed substantial. Energy in steel products is the average nationwide and includes differences in blast furnace or other furnace methods, differences in ore quality, and differences in location of facilities.

Material	Unit	Embodied energy (Btu/unit)	
		Before delivery to jobsite	After delivery to jobsite
Concrete block (8 by 8 by 16 inches)	Each	29,018	31,821
Ready-mix concrete	Cubic yard	2,584,938	2,594,338
Quick lime	Ton	6,394,720	6,867,465
Hydrated lime	Ton	8,812,374	9,463,852
Dead burned dolomite	Ton	9,077,302	9,748,365
Gypsum building materials	Ton	6,189,370	6,970,088
Mineral wool insulation			
Loose fiber	Ton	11,426,830	12,826,171
Batts, blankets, and rolls (3 1/2 inches thick)	Square foot	6,112	6,860
Primary iron and steel			
Pig iron	Pound	7,075	7,444
Carbon steel sheet, hot rolled and enameled	Pound	15,965	16,803
Carbon steel sheet, galvanized	Pound	26,458	27,836
Hot rolled bars and shapes			
Carbon steel	Pound	17,808	18,736
Carbon steel reinforcing bars	Pound	14,888	15,664
Alloy steel, plates and structural shapes	Pound	25,577	26,910
Wire for prestressed concrete	Pound	42,423	44,633
Carbon steel nails and staples	Pound	32,331	34,016
Steel wire, plain	Pound	29,635	31,179
Steel wire, galvanized	Pound	32,683	34,385
Concrete reinforcing mesh (welded wire)	Pound	22,989	24,187
Carbon steel pipe	Pound	24,535	25,813
Stainless steel			
Sheets, hot rolled	Pound	76,814	80,816
Sheets, cold rolled	Pound	131,449	138,298
Bars, hot rolled	Pound	149,454	157,241
Bars, cold finished	Pound	183,579	193,144
Wire	Pound	228,046	239,927
Fabricated metal products			
Fabricated structural steel	Pound	21,711	22,707
Primary nonferrous metals			
Aluminum¶			
Plate	Pound	113,049	115,567
Sheet	Pound	94,596	95,943
Rolled bars and structural shapes	Pound	90,852	92,146
Screw machine products			
Hex nuts, lag screws, and bolts, studs, and threaded rods	Pound	22,474	26,625
Rivets, 1/2 inch and over	Pound	14,640	17,344

*Negligible differences in energy embodiment of rough versus dressed lumber are assumed to be a function of market conditions rather than difference in industrial process. The average has been assumed to be accurate. †These figures relate to "average" units. A general investigation of prefabricated wood doors and windows indicates that an average window is approximately 3 feet wide by 4 feet high, and an average door is 3 feet wide by 6 feet 8 inches high. An average garage door is 8 feet wide by 7 feet high. ‡Hardwood plywood has face veneers shipped long distances, while softwood plywoods are manufactured close to the softwood forests. The price differential is often dependent on market conditions rather than process. §Construction paper is sold in rolls by the square (100 square feet) at an average weight of 5 pounds per square for one-ply paper and 10 pounds per square for two-ply paper. ||On an average, 1 gallon of paint will supply one coat of paint for 300 to 350 square feet of exterior wood or masonry wall, 475 square feet of interior wood or masonry wall, 475 square feet of interior wall or trim, and 525 square feet of exterior trim. ¶Average energy values, including differences in bauxite quality and use of recycled metal.

model to develop a detailed analysis of the ways in which energy, starting as primary energy resources in the ground, progresses through various stages of production and becomes embodied in a completed building. We have established the amount of each primary energy resource (coal, crude petroleum, and electricity generated by using nonfossil fuel methods) required by direct or indirect supply sectors to new building construction. We have also determined the energy embodied directly and indirectly in the materials and services provided directly to new building construction for

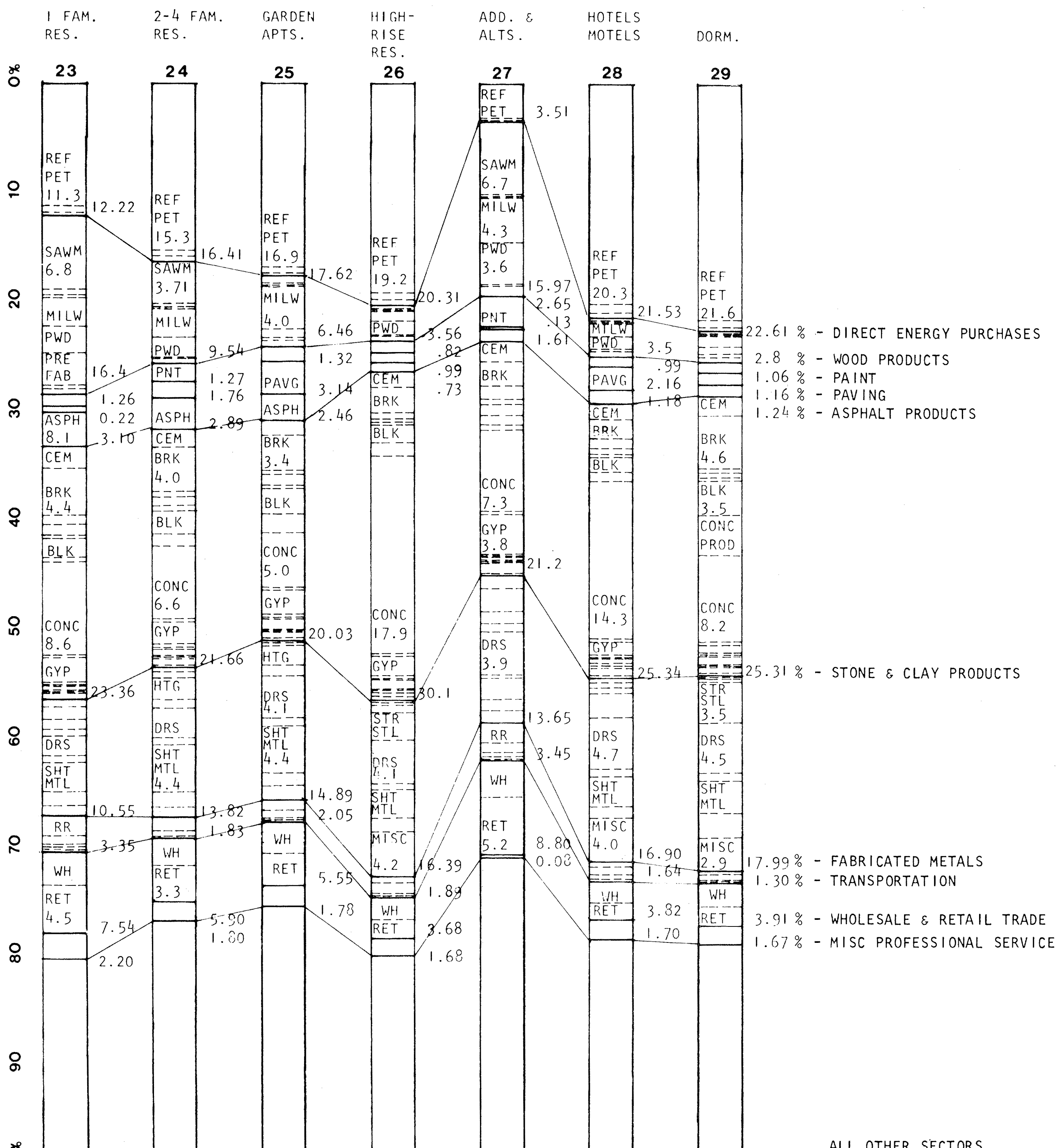


Fig. 3. Total energy allocated among direct purchases of goods and services for seven typical new building construction sectors (1967). Abbreviations: *FAM*, family; *RES*, residence; *APT*, apartment; *ADD*, additions; *ALTS*, alterations; *DORM*, dormitories; *REF PET*, refined petroleum products; *SAWM*, sawmill products; *MILW*, millwork products; *PWD*, plywood products; *PREFAB*, prefabricated wood structures; *ASPH*, asphalt; *CEM*, cement; *BRK*, bricks; *BLK*, concrete blocks; *CONC*, concrete; *GYP*, gypsum products; *DRS*, metal doors; *SHT MET*, sheet metal work; *RR*, railroad; *WH*, wholesale trade; *RET*, retail trade; *HTG*, heating equipment; *PAVG*, paving; *STR STL*, structural steel; *MISC*, miscellaneous metal work; *PNT*, paint products; *NON FER WIRE*, nonferrous wire; *CONC PROD*, concrete products; *PROF SERV*, professional services.

incorporation into completed buildings.

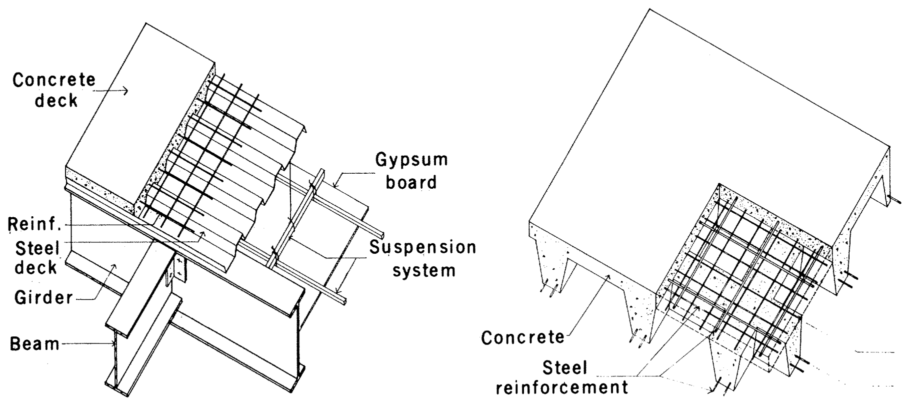
Connecting these two poles of the system are an unknown number of interindustry transactions. When quantified, this number will describe the flow of energy from primary resources to new buildings. The purpose in establishing this network is not only to assess the impact of conservation strategies within contributing industries on the energy embodied in construction, but also to permit the identification of nodes in the system which may become control or limiting points for alternative material strategies. Some nodes, such as machine tool production, may not appear in industries selling to final new building construction demand; nevertheless, they may be large direct and indirect users of energy because of their own consumption of fabricated steel, ready-mixed concrete, and other products requiring sophisticated plants and equipment.

Thus, it will be possible to evaluate changes at any point in the eventual delivery of goods and services to new building construction with respect to the impact they will have at any other critical point, and also to identify substitute materials that would not create unacceptable nodal conditions or excessive demands for primary energy. Shifts can be determined in the total quantity of raw energy and in the type of energy resource involved as a result of material substitution. Conversely, given shifts in the availability of energy resources, it would be possible to determine the changes required in industries within the system in order to provide the materials necessary to continue new building construction.

Policy and Recommendations

We believe that the government could provide a strong stimulus to energy conservation in the construction sector, expanding its program that now deals exclusively with energy use in building operation. Policy should be developed along the following lines.

Energy conservation. For new buildings we believe a target reduction of 20



Standard steel construction		Reinforced concrete construction
	Energy (Btu's)	
244,637,295	Embodied in materials production	150,352,300
18,813,139	Embodied in margins*	4,466,449
263,450,434	Total in materials at jobsite	154,818,749
292,723	Total per square foot	172,021
	Labor (man-hours)	
300	Embodied in materials production	112
39	Embodied in margins*	19
191	Embodied in on-site labor†	380
530	Total	511
0.59	Total per square foot	0.57

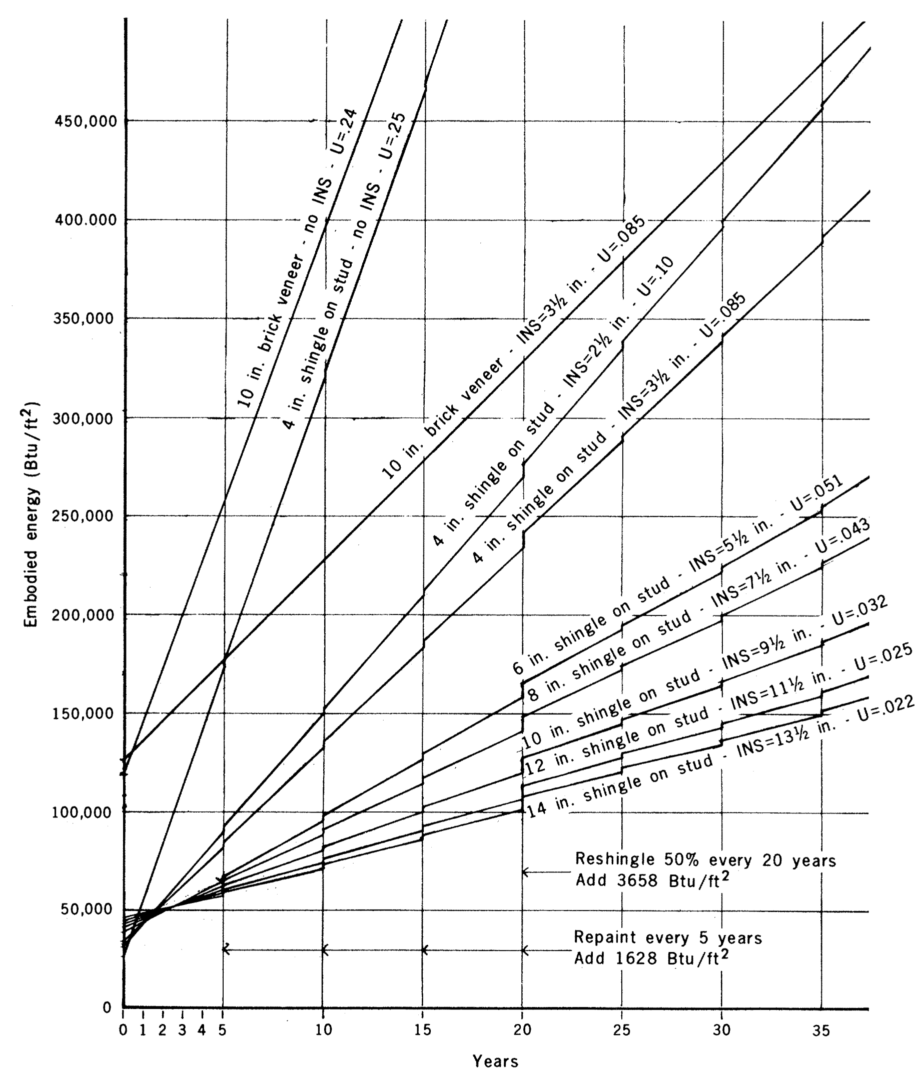


Fig. 4 (top). Comparison of energy and employment requirements for interchangeable structural floor systems measuring 30 by 30 feet or 900 square feet (1967). (Left). Standard steel construction. (Right). Reinforced concrete construction. (*) Trade and transportation activity in delivering unit to construction jobsite from expanded model (†) From (*18*) and (*19*). Fig. 5 (bottom). Energy cost life cycle: mineral wool insulation in wood frame walls in the New York area (1967).

Table 4. Comparison of embodied and annual operational energy for two alternative one-family residence shells.

Description	Standard one-family residence			Modified one-family residence		
	Dimensions*	Energy embodied (Btu)	Annual energy demand (Btu/ft²)	Dimensions*	Energy embodied (Btu)	Annual energy demand (Btu/ft²)
Floor area	1500 ft²			Same		
Roof area	1500 ft²			Same		
Wall area	10 by 160 ft perimeter (1600 ft²)			Same		
Windows	23 at 3 by 4 ft (276 ft²)	1,070,652 (each)	131,477	Same	1,242,852 (each)	67,484
Doors (exterior)	2 at 3 ft by 6 ft 8 in. (40 ft²)	346,502 (each)	131,477	Same	346,502 (each)	131,477
Walls		32,286 (per ft²)	9,889		34,670 (per ft²)	5,934
Studs	2 by 4 in. at 16 in. on center			2 by 6 in. at 24 in. on center		
Exterior finish	Wood shingle			Same		
Interior finish	1/2 in. gypsum board			Same		
Insulation	3 1/2 in. rock wool			5 1/2 in. rock wool		
Window glazing	Single-glazed			Double-glazed		
Roof		68,037 (per ft²)	8,726		76,303 (per ft²)	2,443
Rafters	2 by 12 in. at 16 in. on center			Same		
Roofing	Built-up (on plywood)			Same		
Ceiling	1/2 in. gypsum			Same		
Insulation	5 1/2 in. rock wool			11 1/2 in. rock wool		
Total embodied		171,777,724			188,250,380	
Total conducted			60,527,708			35,168,420
Infiltration			41,800,000			41,800,000
Grand total		171,777,724	102,327,708		188,250,380	76,968,420

*Total dimension, 30 by 50 ft.

percent in total energy consumption is possible. In 1967, this would have meant a reduction in total national energy consumption of 1 percent, or about 670 trillion Btu's. This amount of energy is equivalent to more than 115 million barrels of crude oil, nearly half the amount we imported from Saudi Arabia in 1975, and is greater than our total imports of crude oil in 1975 from Iran (*32, 33*).

We suggest that the government should require energy budgets for the construction of buildings to be set up in state building codes, similar to the requirements that new buildings be designed to operate within prescribed energy budgets, varying according to building type and local climatic conditions. This mandatory requirement could be applied immediately to new government buildings and to new buildings benefiting from government funding or loan-guarantee programs.

Allowing energy prices to approach their replacement costs, by taxing energy at its source or deregulating present energy prices, or a combination of both of these methods, would be a strong economic incentive to reduce the amount of energy used in construction. This circumstance would stimulate improved technology in manufacturing with a greater use of recycled materials, the introduction of heat-reclamation devices in industry, better thermal performance of industrial buildings, and a greater use of cogeneration.

Through the new National Institute of Building Sciences, investigations should be undertaken immediately leading to the refinement of structural analysis and design methods that would result in reductions in the amount of structural material used in buildings.

A national policy of loan incentives and tax credits should be established to encourage the reuse, rehabilitation, and recycling of old and historic buildings—taking advantage of the very large energy investment already made in these buildings and of their infrastructure (roads, water, sewer lines, electric service, and the like). In applying these benefits, provisions should be made to assure that energy needed to operate the recycled buildings is comparable to (generally not greater than) that of new buildings for favorable life-cycle energy use.

Employment. Given the fact that full employment is an important goal for our society, the government should be concerned with the labor impact of energy conservation policy. We have shown that new construction is generally less labor-intensive than maintenance and repair activities; also, that the total labor cost of specific building assemblies can be determined. The government can, therefore, remain aware of the labor impacts associated with the energy strategy described previously and take appropriate measures to aid in relocating and retraining people when energy conservation policies cause a shift from one area of employment to another.

Consumer protection. Since the objective of consumer protection is to provide better products at lower cost, the reduction of unnecessary energy costs in building products is clearly in the consumer interest. In addition to the government requirement for more efficient energy performance in the operation of buildings, the overall government program to reduce energy in the building process should also be designed to reduce the dollar cost of construction.

By approaching energy conservation in construction in these ways, the government could apply overall constraints to the system without getting involved in the minute details of the construction process. Industry and consumers will adjust to the changing importance of energy and will consume correspondingly less of it.

The construction industry is already altering its approach to building in response to the need for lowering the cost of energy used for operational purposes. The new importance of conserving energy in construction will lead to the introduction of new materials, components, assemblies, and building forms that will perform as required with less embodied energy. The development of new products for the retrofitting of existing buildings can be expected, along with the growth of a branch of the contracting industry geared to perform this work.

The energy-intensive industries which supply goods and services to the construction sector would also be faced with rising energy costs and declining demand, and would adjust their energy consumption appropriately. Ultimately, consumers themselves (including government) would ensure the reduction of energy consumption in buildings through their own response to rising energy prices and legislated standards covering the lifetime energy costs (direct and indirect) associated with constructing and operating buildings.

References and Notes

1. The Energy Conservation and Production Act of 1976 (PL 94-385) has stimulated this area. Titles III and IV of this act recognize the significant operational energy cost of buildings and call for the development and application of "energy conservation performance standards" for new and existing buildings at the federal, state, and local levels.
2. B. M. Hannon, R. G. Stein, B. Z. Segal, D. Serber, C. Stein, *CAC Doc. No. 228* (Center for Advanced Computation, University of Illinois at Urbana-Champaign, February 1977).
3. B. Hannon, *Science* **189**, 95 (1975); R. Bezdek and B. Hannon, *ibid.* **185**, 669 (1974); B. Hannon and R. Bezdek, *Eng. Issues* **199**, 521 (1973).
4. C. W. Bullard III and R. A. Herendeen, *Proc. IEEE* **63**, 484 (March 1975).
5. *Survey of Current Business* (Bureau of Economic Analysis, U.S. Department of Commerce, February 1974), vol. 54, No. 2.
6. D. Amado, *CAC Tech. Mem. No. 77* (Center for Advanced Computation, University of Illinois at Urbana-Champaign, September 1976).
7. D. Merrill, *U.S. Employment for 368 Input-Output Sectors for 1963, 1967, and 1972* (Rep. UCID-3757, Lawrence Berkeley Laboratory, University of California at Berkeley, June 1975).
8. Since a 400-level breakdown for labor requirements is not yet available, a slightly less detailed one (357 industries) was used in this study.
9. The actual figure, 10.82 percent, of 7.25 quadrillion Btu's, represents the energy requirement for the total output of construction in 1967, including interindustry and final demand sales. Considering only final demand requirements, construction accounted for 9.42 percent of the U.S. energy requirement. The difference is due to interindustry sales by some maintenance sectors. Since such activity (repair of a steel mill roof, for example) is in fact construction, we allocated corresponding energy requirements to the construction industry, thus arriving at the higher energy requirement figure. An approach such as this, which would produce duplication in a study of several different industries, is sound for this analysis, in which only the construction industry is considered.
10. We did not examine the energy savings that might be realized through more precise structural design. We did not consider reductions in the size of buildings required to serve given programmatic purposes, or the recycling of buildings, where suitable, as alternatives to the construction of new buildings. These approaches would also reduce the amount of energy consumed in building construction. Work has begun on a model that traces the flow of energy from primary resources through the economic system and into the construction of new buildings. When completed, this energy-flow network will identify critical energy nodes in the chain of production.
11. Because of space limitation for this article, the methodology used in connection with the input-output model is omitted here. Details are available from B.H. on request. Data for 1967 are the most recent actual figures available.
12. One British thermal unit is equivalent to 1055 joules.
13. F. W. Dodge Co., *Dodge Construction Statistics, United States Summary Bulletin for December* (McGraw-Hill, New York, 1967).
14. U.S. Bureau of the Census, *1967 Census of Agriculture*, vol. 14, *Farm Finance* (Government Printing Office, Washington, D.C.).
15. Energy profiles were determined by allocating the total energy required by each construction sector among its purchases from all other sectors.
16. B. M. Hannon, R. G. Stein, B. Z. Segal, P. F. Deibert, M. Buckley, D. Nathan, *Energy Use for Building Construction Supplement* (Rep. C00-2791-4, U.S. Department of Energy, Washington, D.C., October 1977).
17. For energy inputs here we use a slightly expanded definition of direct input, which includes the cost of direct and indirect energy. This is useful for distinguishing energy inputs from nonenergy inputs in relation to construction activities.
18. U.S. Bureau of the Census, *1967 Census of Manufacturers* (Government Printing Office, Washington, D.C., 1971), vols. 1 and 2.
19. The expanded energy input-output model does not account for human energy expended for labor, solar energy which has driven the photosynthetic process in wood and fiber formation, the energy embodied in food, clothing, housing, or transportation required to sustain the labor force.
20. Structural analysis and computations by R. Silman and D. Carbonelle of Robert Silman Associates, New York, N.Y.
21. Information on average hourly wages for 1976 and average hours worked per week in 1967 received in conversations with staff of the U.S. Bureau of Labor Statistics.
22. McGraw-Hill Information Systems Co., New York City, *1976 Dodge Construction System Cost* (McGraw-Hill, New York, 1976).
23. A closer examination of both energy and labor embodiments indicates that the high indirect energy and labor intensity of steel is due not only to an extremely energy-intensive manufacturing process but also to a proportionately large amount of trade and transportation activity. A change in design philosophy toward a conscious use of regional materials could be expected to lower both the energy and labor embodiments of the steel alternative.
24. The U-factor indicates the number of British thermal units which will flow through 1 square foot of a material or assembly in 1 hour when there is a temperature difference of 1 degree Fahrenheit on opposite sides of the unit.
25. U.S. Bureau of the Census, *Statistical Abstract of the United States: 1971* (Government Printing Office, Washington, D.C., 1971).
26. The number of heating degree-days for a given day equals 65 minus the average temperature (Fahrenheit) for that day. The underlying assumption is that one must start up a heating system at 65°F (outside) in order to maintain a temperature of 68°F inside.
27. Data from the National Climatic Center, Asheville, N.C. Average regional weather data (for period of July 1931 through June 1976) weighted in accordance with regional population characteristics.
28. U.S. Department of the Interior, *Minerals Yearbook* (Government Printing Offiice, Washington, D.C., 1969), vol. 1.
29. Pope, Evans & Robbins, Inc. and Richard G. Stein & Associates, *Energy Conservation Study—State Office Building Campus, Buildings 8 & 12, Albany, New York*, for State of New York Office of General Services, Albany, June 1975.
30. These recommendations are now being implemented by New York State.
31. U.S. Government General Services Administration, *Energy Conservation Guidelines for New Federal Government Office Buildings*.
32. D. Simpson and D. Smith, *CAC Tech. Mem. No. 39* (Center for Advanced Computation, University of Illinois at Urbana-Champaign, January 1975).
33. U.S. Bureau of the Census, *Statistical Abstract of the United States: 1976* (Government Printing Office, Washington, D.C., 1976).
34. Bureau of Economic Analysis, U.S. Department of Commerce, personal communication.

35. This article resulted from collaboration between Richard G. Stein and Partners, New York, and the Energy Research Group at the Center for Advanced Computation, University of Illinois at Urbana-Champaign. The work was funded by the Office of Energy Conservation of the U.S. Department of Energy and monitored by M. Savitz. We thank R. E. Smith and V. Soltys for their assistance.