Risk with Energy from Conventional and Nonconventional Sources

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Summary. Risk to human health was compared for five conventional and six nonconventional energy systems. The entire cycle for producing energy was considered, not just part. The most important conclusion drawn is that the risk to human health from nonconventional sources can be as high as, or even higher than, that of conventional sources. This result is produced only when the risk per unit energy is considered, rather than the risk per solar panel or windmill. The risk from nonconventional energy sources derives from the large amount of material and labor needed, along with their backup and storage requirements. Risk evaluation is a relatively new discipline, and therefore the results presented here can be considered only a beginning. However, society should keep relative risk in mind when evaluating present and future energy sources.

For each type of energy production there is a risk, and it may be defined as the magnitude of health and safety consequences times the probabilities of these consequences. More practically, in energy production, the risk to human health is accidents and disease resulting in injury or death. This risk is part of the social costs of energy production, which include air and water pollution, land abuse, depletion of resources, and other factors.

The risks associated with so-called conventional energy sources—such as coal, oil, nuclear power, and natural gas—have been compared. However, in the past few years there has been an upsurge of interest in "nonconventional" or "renewable" energy sources, such as solar, wind, methanol, and ocean thermal gradient. An indication of this interest is shown by the approximately 750 abstracts on solar energy alone in a recent annual survey of energy studies (*1*). Nonconventional sources—defined as those not now producing large amounts of energy—are frequently characterized as benign or soft (*2*). The object of this article is to evaluate and compare risk arising from major existing or proposed energy sources, both conventional and nonconventional. It also summarizes information contained in a longer report (*3-11*), and extends risk analyses that have been made in recent years on conventional systems (*12*).

Many individuals, when thinking about energy risk, conclude or assume that such risk is, by and large, due to operation of an energy facility. For example, consider the risk of nuclear accidents or air pollution. My study shows that when the entire fuel or energy cycle, rather than only one part of it, is evaluated, the risks from nonconventional energy systems can be substantially higher than those of some conventional systems.

Main Assumptions

Eleven methods of generating electricity or energy were considered. Five were conventional sources: coal, oil, natural gas, nuclear, and hydroelectricity. Six were nonconventional: solar thermal electric, solar photovoltaic, solar space heating, methanol, wind, and ocean thermal. To put the systems on an equal basis, a unit energy output of 1 megawatt-year was assumed for each.

There are, of course, many other energy systems in public prominence. Some of them depend on shale oil, tar sands, wave energy, tidal energy, coal gasification, large-scale wood burning, geothermal energy, nuclear fusion, garbage-burning, and so-called breeding in nuclear reactors. These are not considered here because one or more components of essential data were not available, often because no models or prototypes have been analyzed. As is noted below, a wide variety of data on materials and labor requirements, public risk, and other factors were needed to perform a complete calculation for each system. If and when full data are available for any energy system not evaluated here, it should be possible to evaluate its overall risk by the methodology described here.

All but two of the energy systems were assumed to produce electricity as the final product. For solar space heating, the thermal energy produced was taken to correspond to the electrical energy that would have been required to heat a building; such an assumption leads to an underestimation of risk from this system by a few percent. For methanol, it is assumed that the mechanical energy it produces is equivalent to the electricity that could have been used to drive vehicles.

The example of solar space heating is an illustration of my general tendency or policy to give nonconventional energy systems the benefit of the doubt, in terms of risk, wherever possible. This policy was adopted to avoid any claims of inadvertent bias. Further examples include assigning lifetimes to nonconventional systems much longer than has been experimentally proved and assumptions of capacity (or load) factors probably higher than justified.

Public attention to risk is often focused on past or potential catastrophes. Release of radioactivity from nuclear reactors, failure of oil or gas pipelines, bursting of hydroelectric dams—these are what capture headlines. It is customary to notice one event that kills 100 people rather than to notice 100 events that each kill one person.

Catastrophes do take place. The actual or estimated risk to the public of dam failures and accidents at reactors, while low, can never be zero. However, as is shown below, the largest proportion of risk to human health from all the energy systems considered is either from industrial and occupational sources or pollution effects. That is, risk generally is incurred by one person or a small group.

In the calculation of overall risk, that resulting from catastrophes is added to that of a noncatastrophic origin. In one sense, apples are being added to oranges, but in another sense like things are being added, since the cost to society, as measured by the number of deaths, is the same. The risk of both catastrophic and noncatastrophic sources has been described (*3*).

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The data used were generally from the United States, although much information on solar space heating, hydroelectricity, and methanol were from Canadian sources. Inevitably, data applying to only one or two countries are limited in scope. However, a study of this type can, in principle, be applied to other nations if appropriate data substitutions are made.

Data sources were of at least three major types: statistics on (i) health damage due to pollutants, (ii) industrial accident and disease statistics, and (iii) materials and labor used for energy systems. Health effects probably do not differ internationally, in that they are based presumably on human biology. Industrial accident rates can vary between industries and nations (*13; 14*, p. 22). Because these rates are not always as disaggregated by industry as in the United States, application of the methodology described here to other countries may require approximations (*15*). Finally, while materials and labor requirements are generally known for conventional systems like coal or nuclear power, our knowledge is less for nonconventional systems. In consequence, one model, believed to be representative of nonconventional systems, was chosen. If another model of solar panel or windmill were chosen, it is possible that the results would be somewhat different from those shown here. Only further research can resolve this question.

Some risk data are controversial. In particular, health effects of fossil fuel burning are not known to a high degree of accuracy (*7, 9*), and this is reflected in the wide error bars (as is shown later) for public risk due to these systems. Even more controversy has been produced by the Rasmussen report (*10*) on light water nuclear reactor safety and public risk. The report has recently been reevaluated because of the criticisms directed toward it (*16*). To avoid any bias in favor of nuclear power, I used the highest values of public risk from reactors taken from a wide number of sources (in some of these, Rasmussen's values were used). This procedure was not followed for other energy systems.

An important assumption is that present-day technology, models, and systems, with their corresponding risk, are used. In essence, this compares more established technologies with less established ones, an unavoidable requirement. However, the length of time that an energy system has existed does not necessarily imply anything about its degree of risk. For example, natural gas and coal-burning are both relatively old technologies; in the first, the risk value is low and in the second it is high.

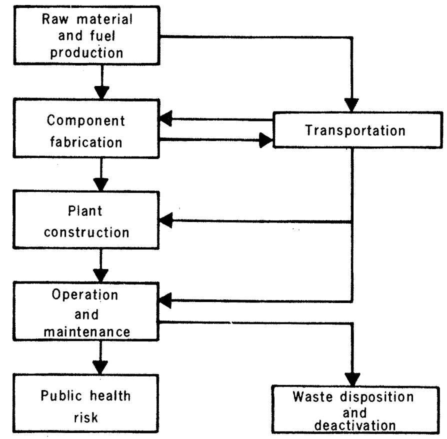


Fig. 1. Sources of risk in energy production. The relative importance of each component depends on the energy system. For example, there will be no fuel requirement for most nonconventional systems. All, however, require raw materials. Public health risk attributable to coal will be primarily from air pollution, and that attributable to nuclear power from the possibility of reactor accidents. Transportation plays a crucial part in many components.

Reliance on present-day technology avoids the need to assume that the future will take any particular course. Risk for some conventional energy sources is to a large degree dependent on the effects of pollution they release. Pollution standards may change. Breakthroughs may be made in wind or solar technology, accompanied by a reduction in the amount of steel, glass, and other materials required, and, therefore, the risk may also be lessened. In my study, I do not assume breakthroughs for some technologies and not for others, as has sometimes been done for other energy analyses.

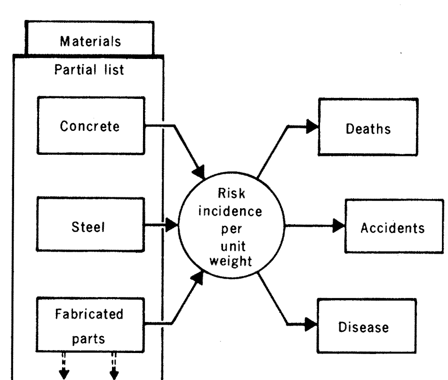


Fig. 2. Risk from material acquisition. Each of the materials that go into an energy system has an associated calculable risk. The risk depends on the accident, illness, and death rate per unit weight produced in the appropriate industry. For example, on average a ton of steel has associated with it a determinable number of deaths, accidents, and diseases. The dashes indicate that other materials are used. A similar diagram can be shown for construction risk.

Making comparisons between energy systems requires a knowledge of their relative efficiencies. Between 30 and 40 percent of the energy produced at a thermal power station is delivered to the consumer as usable power. Apart from transmission losses, almost all the power generated by solar electricity plants would be deliverable to the consumer. The following calculations take these efficiencies into account.

In the last few years the relative advantages of centralization of energy sources has been the subject of much discussion. Some commentators have suggested inherent positive features of decentralized systems like solar space heating. These features were claimed to include lower cost, greater reliability, and less dependence on political and economic authority. However, the analyses here show that low risk is not inherent in decentralized systems. Highly centralized systems such as natural gas and nuclear power production have a far lower risk than do decentralized systems like solar space heating. While decentralized systems may offer political and economic benefits, an inherently low degree of risk to human health is not one of their advantages.

For the purposes of the discussions offered here, energy units are given in terms of megawatt-years over the lifetime of the system, occasionally referred to as unit energy. By "lifetime" is meant the average length of time that the system lasts before replacement is necessary. One megawatt-year supplies all the annual energy requirements for 84 Canadians.

Risk Evaluation

Risk evaluation is similar in many ways to energy accounting, in which the energy inputs to a physical system are summed. In risk evaluation, all the risk of accidents, disease, and death incurred in producing a unit of energy are added together.

The seven sources of risk shown in Fig. 1 probably comprise almost all the risk in energy production. These are material and fuel production, component fabrication, plant construction, operation and maintenance, public health, transportation, and waste disposition.

Consider two technologies: solar heating and coal-fired electricity plants. Solar heating requires the mining of copper for tubing, while the coal-fired plant requires the mining of coal as fuel, iron ore for building turbines, and so on. All technologies require raw materials.

The components such as copper tubing, steam turbines, and all other parts of each system are then fabricated. In terms of transportation, raw materials and components must be moved. Transportation is shown as interacting with four components in Fig. 1.

The energy plants are then constructed, incurring further risk. Operation and maintenance of these systems is often overlooked in risk analysis.

Public health risk is produced by some systems, such as coal, oil, and nuclear power. Finally, there is risk inherent in the disposition of waste. Most public attention to this aspect has focused on nuclear wastes, although there have been disasters associated with coal wastes in the United Kingdom.

For the most part, the detailed risk calculation presented is centered on three of the items of Fig. 1—material and fuel production, component fabrication, and plant construction. The calculation proceeds as follows. The amount of materials required to produce a component is determined. The number of man-hours required to produce this material is then found. If construction, rather than material acquisition, is being considered, then the time required to install or build a component is estimated.

Statistics that show the number of deaths, injuries, or time lost due to disease per unit time worked are available. The number of man-hours required per operation is then multiplied by the deaths, accidents, or disease per man-hour to produce the occupational risk. As an example, suppose mining X tons of coal required Y man-years. If the number of man-days lost per year of work is Z, then the number of man-days per ton of coal is YZ/X. The risk associated with each part of the system is added to produce the total (Fig. 2).

Risk of transportation, operation and maintenance, public health, and waste disposition were calculated along different principles. For transportation, estimates were available for risk incurred in conventional energy systems, such as coal (*5*). This risk could be transformed into risk per unit weight of material transported. The risk for other systems is assumed to be proportional to coal risk per unit weight and distance transported.

Operation and maintenance risk has been estimated for conventional technologies (*5*) and for certain nonconventional technologies (*11*). Other systems had their maintenance requirements estimated in analogy to those already well known.

Public health risk fell into two categories, namely, air pollution, by far the largest, and potential catastrophic accidents. Nuclear power and hydroelectricity are generally acknowledged to fall into the latter category, although the risk is small. To avoid inadvertent bias in estimating nuclear public health risk, values from a well-known nuclear critic (*17*) were used as part of the data base.

Risk of waste disposition was calculated for nuclear power. Other energy sources were assumed to have little or no risk from this source.

The risk from nonconventional systems was calculated in the same general way as for conventional systems. However, some points deserve emphasis. First, emissions produced from acquiring construction materials can produce substantial public health risk. This source, derived from coal used in smelting steel, is fairly small for conventional systems. This emission can be called "pre-building" risk, since it occurs before the energy system starts rather than after. Second, some nonconventional energy sources, such as solar and windpower, require comparatively large backup and storage systems when their energy source is unavailable because the

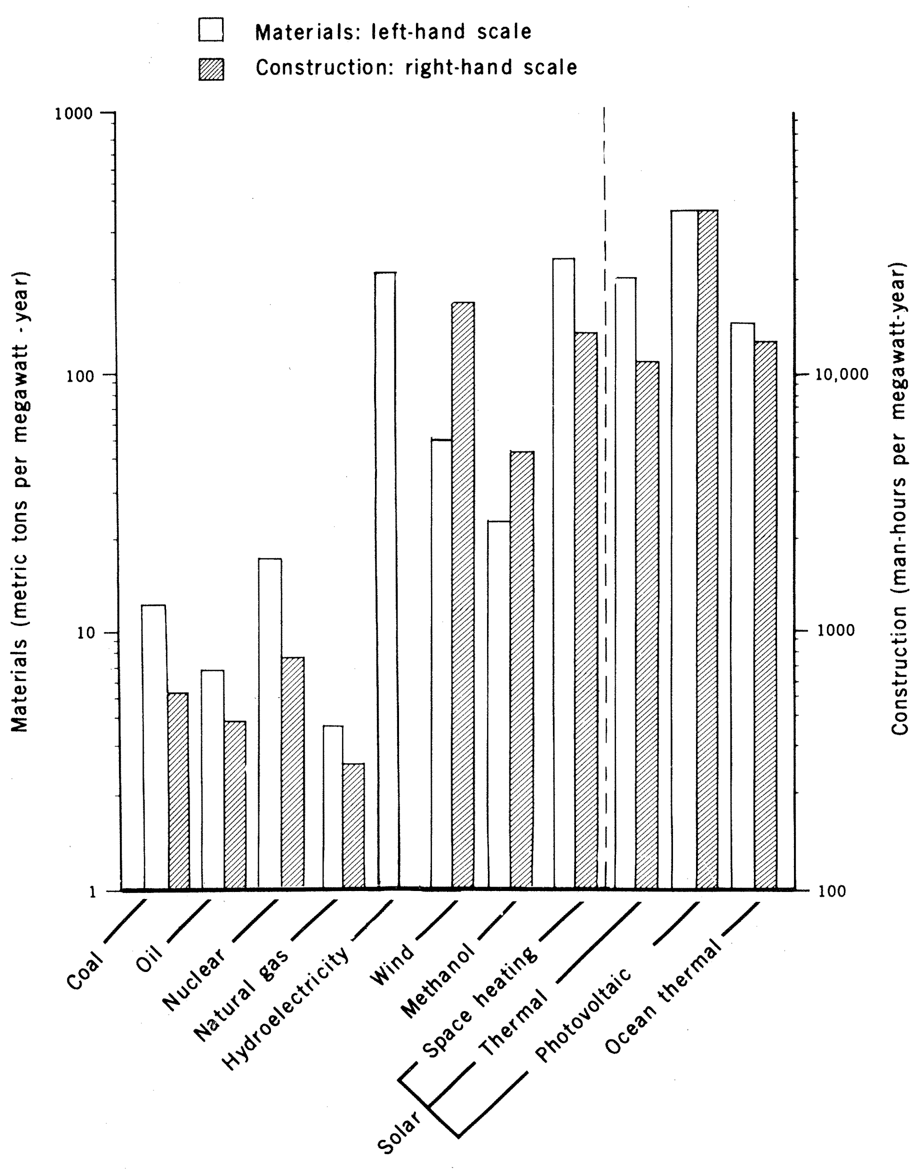


Fig. 3. Summary of material acquisition and construction requirements. Both material and construction time requirements are greater for nonconventional systems as compared to conventional systems. Natural gas has the lowest requirements of both types. Solar photovoltaic has the highest material requirements; the system also has the highest construction times. In this figure, a variety of construction trades and materials are lumped together to provide a simplified overall picture. For example, trades include those of plumbing, electrical work, sheet metal work, and so on; materials include cement, steel, glass, aluminum, and the like. Similar graphs could be devised for particular trades or materials. The ratio between the highest and lowest values in each category is between 100 and 200. Construction time for hydroelectricity is not available.

sun does not always shine and the wind does not always blow. The construction and operation of these storage and backup systems must be taken into account when computing risk. In equalizing energy systems this way, we are following the philosophy of Lovins (*2*):

> compare the total cost (capital and life-cycle) of the solar system with the total cost of the other complete systems that otherwise would have to be used in the long run.

Only by considering storage and backup can we ensure that the Lovins philosophy is carried out.

What energy source should be used for backup? The report of Herrera (*11*), which supported nonconventional energy systems, specified coal for solar thermal electric and solar photovoltaic systems; my estimations are also based on the use of coal in connection with wind, the only other nonconventional system requiring backup. It is also possible to have other systems, such as nuclear power (which is shown to be a relatively low-risk system), used as backup, although advocates of nonconventional energy might find this philosophically difficult. Results of both options are shown in the concluding figures.

How can we compare or combine deaths and less severe health problems, such as accidents and disease-related disabilities? While there is no simple method for assessing the impact of a death, some studies have equated it to 6000 man-days lost (*6, 8*). This simplifying assumption is used here. A sensitivity analysis showed that the ranking of systems in terms of total man-days lost per unit energy was not dependent on the exact value of man-days assigned per death.

The age at death from chronic ailments (disease) is probably higher than that caused by industrial accidents. While this will influence the total number of man-days lost per death, its effect could not be calculated from available data.

Assessing the Results

When the entire fuel or energy cycle is considered, nonconventional energy systems can have substantial risk to human health. This surprising result comes about by considering factors that are sometimes ignored.

The amount of materials used per unit energy output is a significant factor in computing risk. In addition, construction times play a key part (Fig. 3). The first four technologies all have low material use and construction times.

Solar photovoltaic requires large amounts of aluminum and concrete for construction and therefore has the highest material utilization. The weight of materials is 150 percent higher than any other nonconventional technology. It also has the highest construction time. Both material and construction requirements are generally higher for nonconventional as compared to conventional systems. This result will be reflected in higher occupational risk.

Conventional technologies generally have their risk categorized as gathering and handling of fuels, transportation, and electricity production (Fig. 4). Nonconventional technologies had six analogous categories. For simplicity, gathering and handling of fuels in conventional systems was equated with material acquisition and construction for nonconventional systems.

Natural gas incurs most of its risk in gathering and handling fuels. It is followed closely in its proportion of risk from this source by nuclear and ocean thermal. Most of the risk of coal and oil is incurred in electricity production, and is a consequence of air pollution. Only nuclear power has calculated risk due to waste management, constituting about 6 percent of the total. Coal also has waste management risk, due to slag and fly ash, but this is not included in the computations because quantitative data are lacking.

Wind, solar thermal, and solar photovoltaic have much of their risk produced by the backup they require. Ocean thermal has the highest proportion in material acquisition of all the nonconventional systems.

The summarizing figures can be divided into (i) occupational risk, borne by those who construct, fabricate, and maintain the energy sources, (ii) risk to members of the public, and (iii) the total risk, or the sum of the occupational and public risk. Figure 5 shows the occupational man-days lost per unit energy averaged over the lifetime of the system, which for most is assumed to be 30 years. This concept is used to average the initial construction risk over the lifespan. The maximum number of occupational man-days lost results from methanol, followed by windpower. Two other nonconventional technologies, solar thermal and photovoltaic, follow. Lowest is natural gas, followed by nuclear. For most of the nonconventional systems, the cause of large values is high material acquisition and construction risk.

Figure 6, showing risk to the public, is different. Two of the conventional tech-

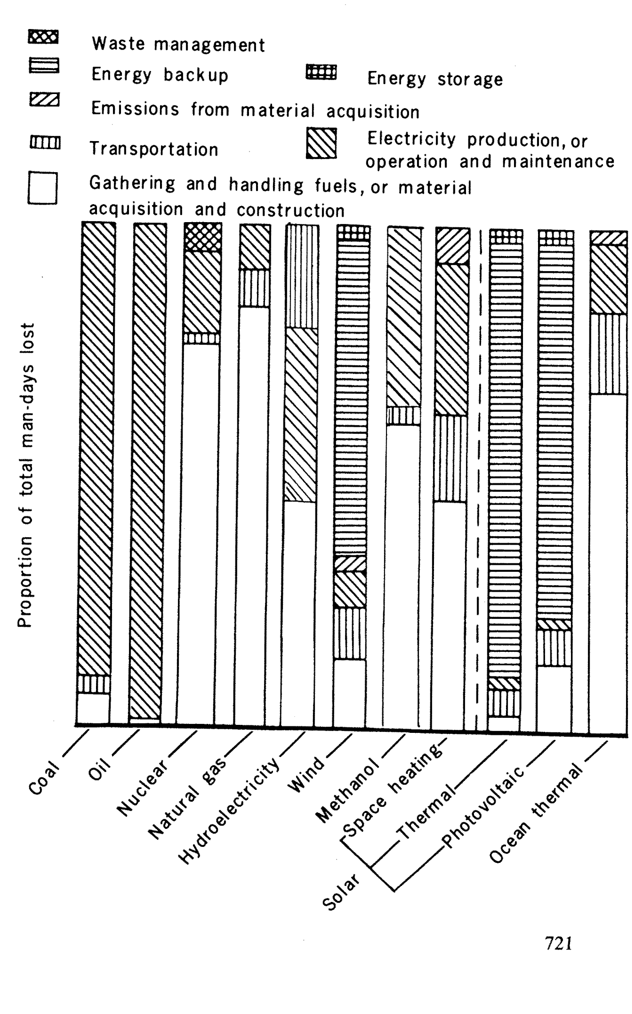


Fig. 4. Proportions of risk by source. Sources of risk vary considerably from one energy system to the next. The maximum value of the range for each component of total risk was used. A similar graph could be constructed for minimum values of the range. For coal and oil, most of the risk is due to electricity production (air pollution), whereas for natural gas, nuclear sources, and ocean thermal sources most of the risk is due to fuel or material acquisition. Wind, solar thermal electric, and solar photovoltaic sources have a large risk proportion from energy backup, assumed to be coal. The total risk for each system has been normalized in order to show the differences clearly.

nologies, coal and oil, lead the list because of emissions produced by burning fuel. However, some nonconventional technologies, such as wind, also have relatively high public risk. This risk derives from emissions as well, although not from air pollutants generated from operation. As far as is known, solar and wind systems are pollution-free during normal operation. However, steel is used in building many nonconventional systems, and coal is used in making most steel. Coal is the source of most sulfur dioxide produced industrially, and the pollutant is believed to cause much of the damage to health from polluted air.

A second source of public risk for three of the six nonconventional systems lies in the coal used for backup energy. Figures 5 to 7 show what happens when low risk backup, such as natural gas or nuclear, is substituted. The public risk is reduced substantially when low risk backup is employed, but the relative order of the systems remains about the same (Fig. 6).

The total risk for both occupational

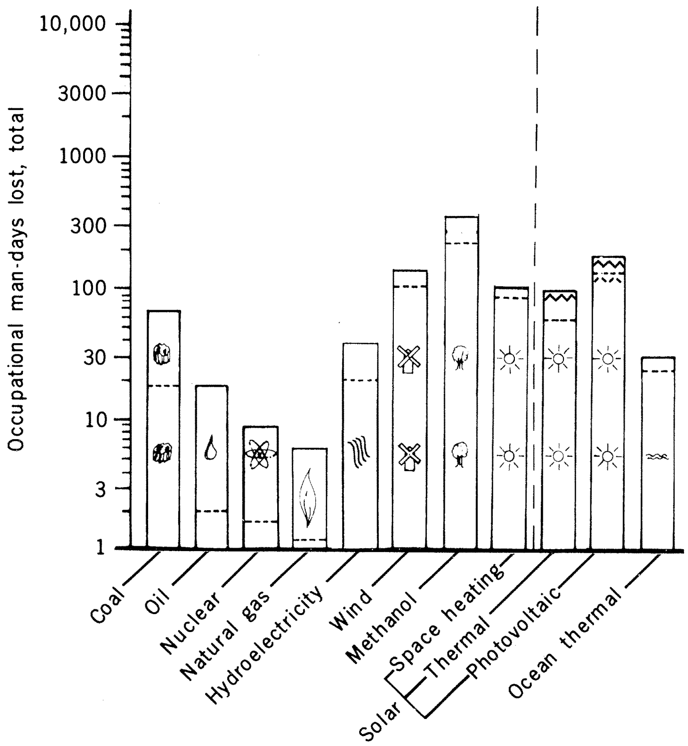
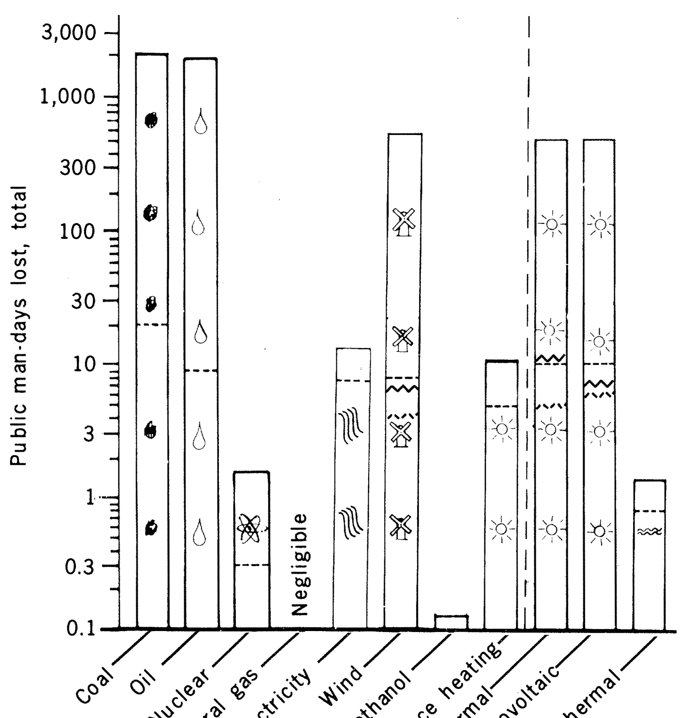
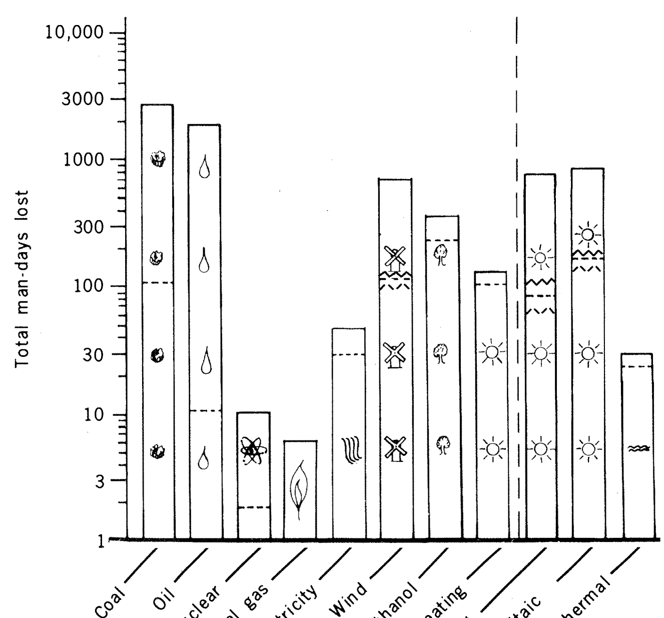


Fig. 5 (upper left). Occupational man-days lost per megawatt-year net output over lifetime of system. The top of the bars indicates the upper end of the range of values; the horizontal dotted lines within the bars, the lower. For example, coal would have a maximum value of about 70 man-days lost per megawatt-year output over the 30-year system life. The jagged lines within the bars indicate values when low-risk backup, such as nuclear or natural gas, is used. Where jagged lines (solid for maximum, broken for minimum) are not shown, values from low-risk backup are similar to those for standard backup. Bars to the right of the vertical dotted lines indicate values for technologies less applicable to Canada, due to climatic conditions. This scheme of notation is followed in Figs. 6 and 7. Most nonconventional systems have higher values than conventional systems. Note the vertical logarithmic scale. Fig. 6 (lower left). Public man-days lost per megawatt-year net output over lifetime of system. (See explanation in legend to Fig. 5). Much of the risk is produced by emissions created after fuel is gathered (for conventional systems) or by production and backup (for nonconventional technologies). Methanol has the lowest maximum of the nonconventional technologies. This is due to the lack of a requirement for energy backup and storage, with their accompanying air pollutants, and the relatively low requirement for materials. Fig. 7 (lower right). Total man-days lost per megawatt-year net output over the lifetime of the system (see explanation in legend to Fig. 5). The public and occupational risk is combined here. Natural gas power has the lowest value, followed by nuclear. Most nonconventional technologies have risk comparable to coal and oil. This somewhat surprising result is due to three factors: (i) the large amount of materials they require, (ii) the risk associated with backup energy; and (iii) risk associated with energy storage.





and public categories is shown in Fig. 7. Because the number of public man-days lost is higher than occupational for most of the systems, it dominates. The total risk from four of the six nonconventional technologies is comparable to that of coal and oil. Only ocean thermal has risk substantially lower than that of the others. However, its risk is about two to three times as high as that of nuclear power, and five to seven times that of natural gas.

The data shown in Figs. 5 to 7 indicate a range of values, rather than a single point. The top of the bars indicate the maxima, and the horizontal dotted lines show the minima. This follows traditions well established in the field of risk (*7, 9*). These traditions have persisted because much risk data are not accurately known. For example, the relation between air pollution and health effects is subject to wide variation. This is shown in Fig. 6, where the maxima and minima for coal and oil vary considerably. In addition, the precise materials, labor, backup, and storage requirements for future standardized nonconventional systems are not known. Those evaluated here are believed to be reasonably representative, but their design may change in the future. The ranges of uncertainty should be kept in mind when these results are evaluated.

Thus, if the entire fuel or energy cycle is considered, nonconventional energy systems apparently have risk to human health substantially different from that expected on the basis of intuition. The results shown do not, of course, imply that a particular technology should or should not be used.

It is entirely possible that the calculated risk values will change in future years. A better understanding of risk and its sources may produce public pressure to reduce it for all energy sources. This could be accomplished by either technological or administrative measures, or both. In addition, personnel using newer energy technology systems will probably become more familiar with their operation, and it is likely that occupational risk will decrease. Design of energy systems may become more standardized than they have in the past, so that the risk due to unfamiliarity will become lower. Other considerations could be listed which may shrink risk values in the future for many energy systems.

These considerations can be applied to particular systems. For example, coal production will probably shift more to strip mining (generally low risk) in opposition to underground mining (generally high risk). Coal slurry pipelines (generally low risk) are being suggested as partial replacements for rail transport (generally higher risk). A similar listing may be made for each of the eleven systems considered.

However, it should not be assumed that all risk will monotonically decrease in the future. As examples of contrary trends, liquefied natural gas, as opposed to the gaseous form evaluated in this article, may pose in coming years public risk that is not negligible. As oil deposits become more difficult to find, the risk associated with each unit of energy will probably rise. Finally, industrial accident rates can rise as well as fall. Of 23 industries reporting injury frequency rates in the United States for 1971 and 1976, 18 showed an increase (*14*, p. 27).

The large differences in risk between many of the energy systems discussed make it likely that, while the absolute values of man-days lost per unit energy will probably change in the future, the relative rankings of systems will not change substantially. Only time and a deeper understanding of these systems can verify this contention.

The field of risk accounting is only beginning. While the risk due to energy generation forms only one part of selection criteria, without this knowledge we cannot make a fully informed judgment.

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