A Review of the Health Effects of Energy Development

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Abstract
Health risks associated with the commercial production of electrical energy from various sources have been estimated by various authors. Recent literature on this topic is reviewed. Commercial energy consumption per capita, a measure of a country's level of industrialisation and technological development, has increased several-fold over the past century. This development has been associated with an average increase of about 35 years in life expectancy in Canada and other industrialized countries. The average health benefits which accrue to the population of these countries outweigh the health risks of the required energy production by a very large factor. The statistical probabilities of mortality from various causes are reviewed.

Résumé
Les risques portés à la santé par la production d'énergie électrique par différentes sources ont été évalués par plusieurs auteurs. La littérature récente sur ce sujet est revue. Depuis le début de ce siècle la consommation énergétique commerciale par capita, une mesure du niveau de développement industriel et technologique, a augmenté de plusieurs fois. Au Canada et en d'autres pays industrialisés, ce développement a été associé à une augmentation moyenne de l'âge de survie d'environ 35 ans. Les bénifices moyens pour la santé résultants pour la population de ces pays dépassent de beaucoup les risques portés à la santé par la production énergétique requise. Les probabilités statistiques des différentes causes de mortalité sont revues.

Introduction

Remarkable social changes have resulted from technological development that has occurred in industrial societies over the past century [23, 40, 41]. Average income in constant dollars has increased markedly, even while the proportion of time spent at work has decreased and the amount of time available for creative and leisure activities has increased. The proportion of societal effort required to produce food for the population has decreased greatly due to the shift to energy-intensive industrial agriculture. Rapid communication and transportation systems have been introduced. Average life expectancy has increased (Figure 1), and the birthrate decreased as the ability of humans to control the circumstances of their life has grown.

Energy production plays a crucial role in technological development and industrial prosperity [5, 37, 41]. The present paper is concerned with the health costs and health benefits of this energy development.

Attributable Health Risks

Observed increases in life expectancy in industrialized societies (Figure 1) have been due largely to increased understanding of the causes of illness and death, and to increased ability to do something to minimize these causes. For example, the discovery that scurvy was attributable to the lack of some nutritional factor led to the use of citrus fruits and later of vitamin C, and to the rapid transportation of fresh produce to consumers, as successful preventive measures. Similarly, the discovery of bacteria and viruses as causes of various infectious diseases led to the application of disinfectants, chlorine in municipal water supplies, pasteurization of milk supplies, improved sanitary standards, and the introduction of vaccines and antibiotics, as successful preventive or therapeutic measures.

Immediate causes of death are currently classified into many different, internationally recommended categories [47]. The broad categories of immediate causes of death in Canada for 1983 are summarized in Table 1. Recent changes in death rates in these categories are indicated in Figure 2. It is apparent that death rates in most categories, except cancer and violent causes, are decreasing.

Keywords: health effects, energy production, nuclear power, energy consumption, life expectancy.

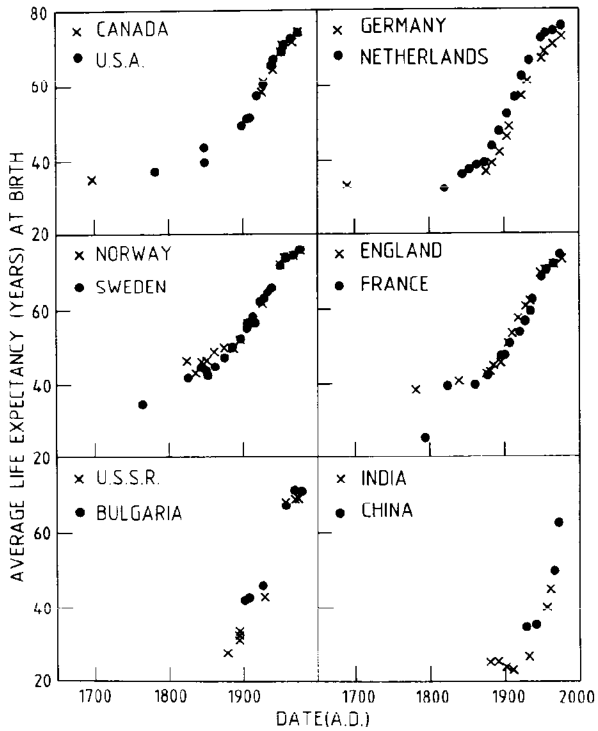

Figure 1 Average life expectancy at birth in various countries. Derivation of data given in Myers *et al.* 1984

For continued improvement in general health and longevity, it is essential to know more about the factors that contribute to these various categories of mortality. This understanding is also required for assessment of the health risks of energy production. Some comment

Table 1: Immediate Causes of Death in Canada, 1983 (Statistics Canada 1985; and Labour Canada 1982)

Cause	*Standardized death rates per* 100,000 — *Male*	*Female*	*% of total*	
Pneumonia, influenza and tuberculosis	22.4	18.8	3.5	
Lung cancer	56.5	17.1	6.2	24.8
Other cancers	113.6	108.4	18.6	
External causes:				
occupational (1980)	6.1	0.2	0.5	
motor vehicle	24.2	9.1	2.8	8.7
suicide	21.1	6.2	2.3	
other	23.5	13.6	3.1	
Cardiovascular diseases	290.7	211.0	42.1	
All other causes	148.3	102.3	21.0	
Total	706.4	486.7	100.	

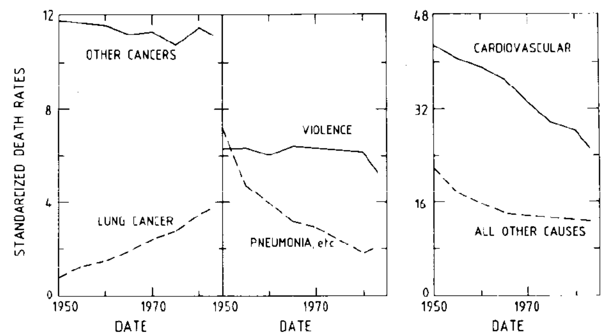

Figure 2 Standardized death rates for various causes of death, Canada 1950–1983. Data from General Mortality 1976, and Statistics Canada 1975, 1980, and 1983.

on factors that contribute to deaths in these categories would thus seem appropriate.

About five per cent of all deaths from violent causes [42] are due to occupational accidents [21]. A small proportion of other deaths from violent causes involve transportation of goods required for energy production. The immediate cause of a violent death is usually obvious and thus reliable statistics on known actuarial deaths attributable to various phases of energy production can be calculated.

In most other categories, the attributable cause of any specific death is less obvious and can only be derived on the basis of statistical probabilities. Considerable effort has been devoted to the quantitative assessment of the health effects of exposure to ionizing radiation [2, 18, 46]. The risk of fatal cancers induced by radiation is generally taken to be about 1.3×10^{-5} per mSv of whole body irradiation. On this basis, average exposures of 2 mSv per year for 75 years from natural sources of ionizing radiation would be responsible for about 0.8% of all fatal cancers in North America. Exposure to ionizing radiation is also believed to contribute to the genetic disorders that require medical attention at some time in a person's life and that can, on occasion, result in premature death; normal background levels of radiation are again thought to contribute about one per cent to the total of these genetic diseases. Estimates of the probability of induction of curable cancers by low doses of radiation are also available.

Combustion products were the first causes of cancer to be identified in the late eighteenth century and, in the form of cigarette smoke, are generally believed to be responsible for most of the recent increase in lung cancer deaths (Figure 2). Quantitative estimates of the risk of lung cancer following inhalation of combustion products have been derived [26, 28, 30, 32]. A small number of other types of fatal cancer can also be attributed to this cause [30]. Exposure to high concentrations of combustion products also contributes to

Table 2: Proportion of Cancer Deaths Attributable to Various Factors (Doll and Peto 1981; see also Wynder and Gori 1977; and Higginson and Muir 1979)

Factor	*Percent of all cancer deaths*
Diet	35
Tobacco	30
Viruses and other infections	10
Reproductive behaviour	7
Occupation	4
Alcohol	3
Pollution	2
Sunlight	2
Ionizing radiation	1
Medical procedures	1
Industrial products	< 1
Food additives	< 1 (a)
Unknown	5 ?

(a) Might also be less than zero allowing for protective effects of antioxidants and other preservatives. Note that most of the percentages given in this table are best estimates which are subject to considerable uncertainty.

premature death caused by non-malignant respiratory diseases [9], but it is uncertain whether or not the probability of these deleterious health effects is proportional to dose, at low levels of exposure. Since the urine of cigarette smokers is known to contain appreciable levels of mutagenic agents [20, 52], it is to be expected that inhalation of combustion products would increase the incidence of genetic disorders in the population; there are however no quantitative estimates of risk for this particular endpoint.

Cancer-causing agents have attracted considerable public attention in recent years. This may be due in part to the fact that more information on causes of cancer is becoming available (Table 2). Some 80–90% of all cancers can be correlated with differences in lifestyle in different societies and social groups, and are thus presumed to be preventable [6, 7]. Moreover, the proportion of all deaths in Canada due to cancer increased from 12% in 1941 to 25% in 1983 (Figure 3). This increase is due largely to successful reduction of other causes of premature death (Figure 2) and the resultant increase in life expectancy (Figure 1) in recent decades.

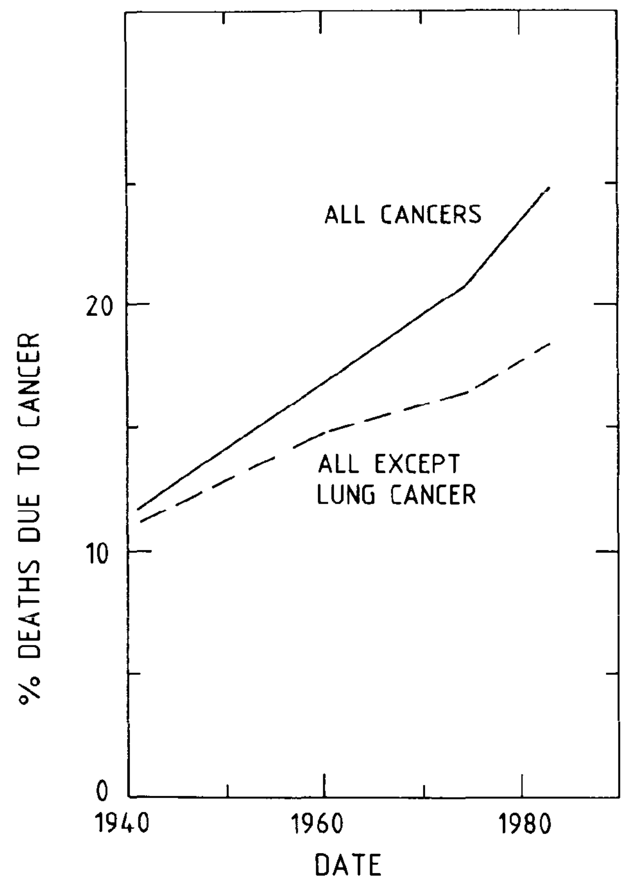

Figure 3 Percentage of deaths due to cancer, Canada 1940–1983. Data from Canada Year Book annual issues; see also references Figure 2.

Health Hazards Associated with Energy Production

Considerable effort has been devoted in recent years to quantitative assessment of the health hazards of energy production, and there have been at least four international scientific conferences within the past eight years concerned with this particular topic. One of the earlier summaries of health hazards of four sources of electrical power is shown in Table 3. Although these assessments continue to become more sophisticated, the general magnitude of the resulting data on hazards has not changed markedly (Tables 4 and 5). The predicted number of deaths attributable to production of electrical power varies from about 0.2–1 per GW·a for safer sources of energy such as nuclear power and natural gas, to about 10–20 per GW·a for more hazardous sources such as oil and coal [29]. These estimates include operations in all phases of energy production, from initial recovery of raw materials through refinement of these raw materials and production of useable energy in power plants, to disposal of waste products. Estimates of the statistical probability of catastrophic accidents, including those

Table 3: Estimated Deaths per GW(e)·a for Electricity Produced from Four Sources (American Medical Association 1978)

	Coal	*Oil*	*Natural gas*	*Nuclear*
Occupational	0.5–8	0.14–1.3	0.06–0.3	0.035–0.9
Public	1.6–306	1–100	—	0.01–0.2
Total (a)	25 (2.2–314)	10 (1.1–101)	0.13 (0.06–0.3)	0.2 (0.05–1.1)

(a) Total deaths given as the geometric mean of the range of values indicated in brackets.

Table 4: One Analysis of Estimated Deaths per GW(e)·a for Electricity Produced from Two Sources (Hamilton 1984)

Process	*Coal* Fatal accidents	*Coal* Occupational disease	*Coal* Public disease	*Nuclear* Fatal accidents	*Nuclear* Occupational disease	*Nuclear* Public disease
Underground mining (a)	1.2–1.5	0.6–1.5	—	0.4	0.2	0.05
Processing	0.03–0.1	—	—	0.006	0.05	0.01
Transport	0.2–4.8 (b)	—	—	0.01	0.001	0.0005
Electr. generation	0.1–0.2	—	15	0.01	0.13	0.12
Waste management	(not tabulated)			0.0001	0.005	0.000001
Total (a)	1.5–6.6	0.6–1.5	15	0.4	0.4	0.2
		17–22			1.0	

(a) Fatalities per unit energy are considerably smaller for surface mining; total deaths per GW(e)·a would become 15–19 for coal and 0.6 for nuclear if the fuel source were extracted by surface mining.
(b) Estimated fatalities depend on the method of transportation of coal, being lowest for transportation by pipeline and highest for transportation by truck.

Table 5: Estimated Deaths per GW·a for a Variety of Energy Sources (Inhaber 1982)

Energy source	*Occupational* Accident	*Occupational* Disease	*Public* Accident	*Public* Disease	*Total (approximate)*
Coal	2.5–6.7	0–0.8	0.8–1.9	17–60	20–70
Methanol	17–18	0.1	0.1–0.3	0.1–0.5	18
Oil	0.3–2	—	—	6–17	6–20
Solar space and water heating (a)	5.5–8.9	0.01–0.04	0.2–0.5	0.4–1.4	6–11
Solar photovoltaic	2–3.4	0.01–0.03	0.2–0.5	1.2–3.6	3–8
Wind	3.6–4.3	0.02–0.04	0.1–0.2	0.5–1.5	5
Hydroelectric	1.5–2.6	—	1.1–1.6	—	3
Solar thermal electric	0.4–0.5	0.03	0.15–0.3	0.6–1.8	1–3
Ocean thermal	1.7–2.3	—	0.03–0.07	0.04–0.1	2
Nuclear	0.3–0.8	0.2–0.8	0.01	0.07–0.5	0.6–2
Natural gas	0.2–0.5	—	0.01	—	0.2–0.5

(a) Values given for solar space heating are per GW thermal energy; all other values in the above table are per GW electrical energy.

that might occur in nuclear power stations with western standards of secondary safety features and containment, are usually included in these calculations. While Chernobyl has been the most noteworthy catastrophic accident in the energy production sector in the past few years, it should be noted that approximately 500 people died after an explosion in a gas storage complex in Mexico City in 1984, over 200 people died when a dam broke in Stava, Italy in 1985, and more than 200 coal miners have died in three accidents in as many years in Japan.

A more detailed comparison of coal and nuclear power is shown in Table 4. The phase of the fuel cycle responsible for the major portion of the health detriment depends upon the energy source. For coal, the major detriment appears to be public hazard from the effluents from coal-fired power stations; for nuclear, the occupational hazards associated with underground mining.

This type of assessment has been extended to a variety of other energy sources [10, 11, 19, 24, 33]. Many of these (hydroelectric and solar power, for example) appear to be intermediate in health hazards per GW·a between coal and nuclear power (Table 5), while

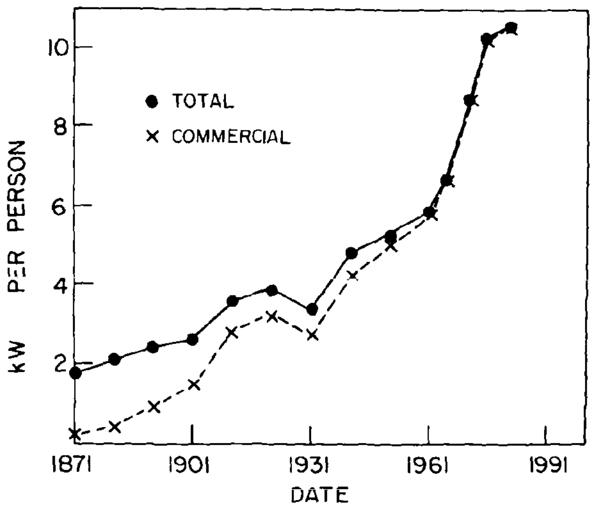

Figure 4 Total and commercial (fossil fuel, hydroelectric power, and nuclear power) energy consumption per capita in Canada, 1871–1981 (Steward 1978). Data for 1981 were extrapolated from United Nations Statistical Yearbook 1981.

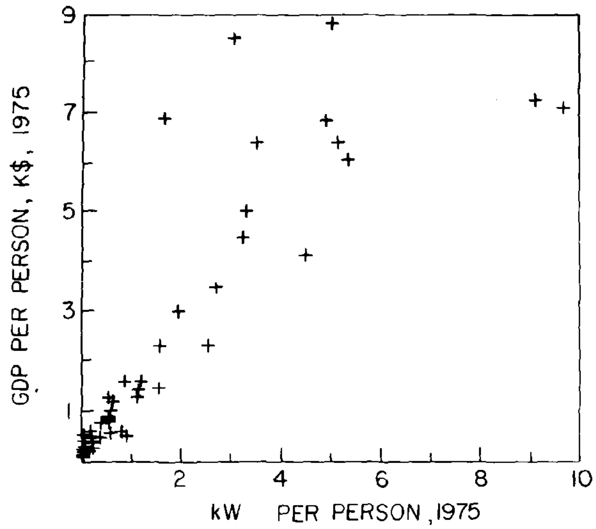

Figure 5 Relationship between commercial energy consumption and gross domestic product per person for various countries in 1975 (United Nations Statistical Yearbook 1981). Data have been converted to kW·a assuming 0.123 tonnes coal equivalent equals 1000 kWh (United Nations Statistical Yearbook 1981).

other traditional sources of heat such as fuel wood are apparently more hazardous than coal-fired power stations [10, 24].

Health Benefits of Energy Production

Technological development and industrial prosperity require affordable supplies of useable energy. In Canada in 1871, this energy was derived largely from fuel wood, animal work, and wind and water-driven mills, with a small contribution from human work. In recent decades, energy has been derived largely from fossil fuels, hydro-electricity, and nuclear power (Figure 4).

Energy consumption in different countries is closely correlated with industrial prosperity and the gross domestic product per capita (Figure 5). A close correlation with per capita purchasing power (income) based on actual costs in local currency of goods and services has also been demonstrated [4]. The plot of life expectancy in various countries in a given year versus commercial energy consumption per capita shows a striking increase in life expectancy, with increases in energy consumption up to about 0.5 kW per person, an intermediate phase in which life expectancy increases more slowly as energy consumption increases, and a mature phase above 2–3 kW per person in which there is little further increase in life expectancy (Figure 6). In this mature phase, nutritional, sanitary, and health care standards appropriate for that time have presumably been put into place in all industrialized countries. However, life expectancy has continued to increase with time in those countries where commercial energy consumption exceeds 2 3 kW per person (Figures 1 and 6). A large portion of this continued increase in life expectancy can be attributed to biomedical research in industrialized countries on causes of disease, and to application of methods to prevent or treat these diseases [25].

Reliable data on the relationship between total energy consumption and life expectancy during the earliest phases of technological development in human

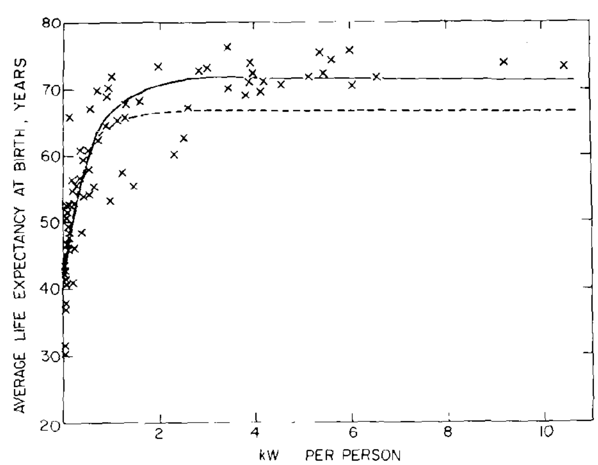

Figure 6 Effect of commercial energy consumption per capita on average life expectancy at birth in various countries. The data points represent the most recent values (usually about 1975) available from United Nations Statistical Yearbook 1981 for countries with more than five million inhabitants. The dashed and solid lines are the curves fitted to similar data for the years 1950 and 1975 respectively (Sagan and Afifi 1978).

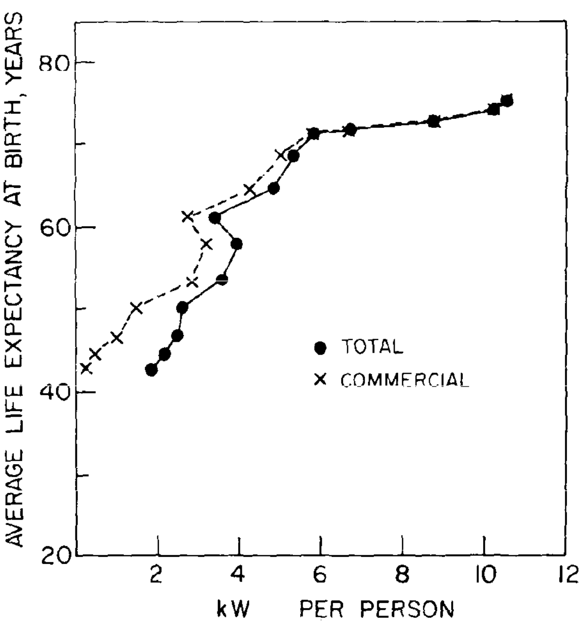

Figure 7 Effect of total and commercial energy consumption per capita on average life expectancy at birth, Canada, 1871–1981 (Steward 1978, and Historical Statistics of Canada 1983).

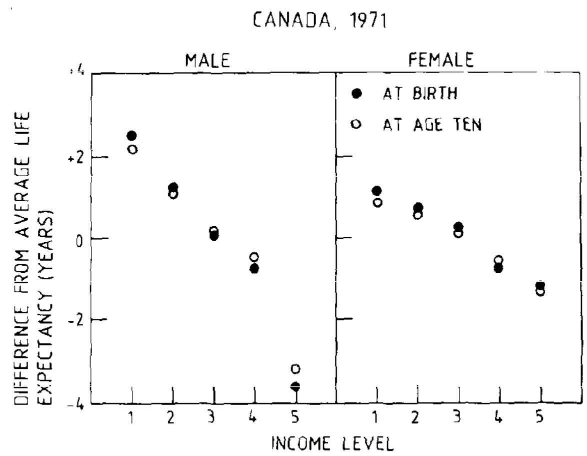

Figure 8 Effect of average household income on life expectancy at birth (Wigle and Mao 1980). Average income levels for groups 1–5 were taken to be 12.1 K, 10.6 K, 9.1 K, 8.0 K, and 6.7 K Canadian dollars, respectively. Each of the five groups contained 20% of the total urban population in Canada in 1971.

history are not available. We do however know that the average life expectancy in Ohio during the period 700–1100 A.D. was about 20 years [22], and that average life expectancy in the same part of the world was about 40 years by 1871 (Figure 1), at a time when total energy consumption was about 2 kW per person (Figure 4). Assuming that energy production under primitive conditions was limited to the work capacity of the human body (i.e., about 0.1 kW per person), the health benefits associated with the earliest stages of societal development would on average be somewhere in the region of 10 years increase in life expectancy per kW energy production per person.

When life expectancy is plotted against energy consumption in Canada over the past 110 years, the data indicate a rapid increase in life expectancy of about six years per kW per person at a time when total energy consumption was increasing from 2 to 6 kW per person; a slower increase, amounting to about 0.7 years per kW, is evident as total energy consumption increased above 6 kW per person (Figure 7). The difference in the slopes of the lines between the earlier and later portions of this century is probably related to two factors: recent increases in energy consumption for material comforts not directly essential for health, and the fact that most of the infectious diseases that can result in premature death of otherwise healthy individuals had been largely eliminated by the 1950s.

Another estimate of the effects of prosperity on average life expectancy in Canada can be derived from Figure 8, which shows deviations from average life expectancy for urban populations in 1971 with different average household incomes. Average energy consumption in Canada at this time was about 8.5 kW per person (Figure 4). Assuming that differences in average income levels will be reflected, directly or indirectly, in proportionate differences in average energy consumption, the data suggest an average increase in life expectancy of 0.9 years (1.2 for males, 0.6 for females) per kW per person between the low and high income urban groups in Canada. It is of some interest to note that this difference in life expectancy (Figure 8) was more closely correlated with income than with average educational levels [49], and continued to exist at a time when there was universal insurance for medical care costs, safe urban water supplies, and compulsory basic education. Similar variations in average life expectancy of high and low income groups in the same community have been demonstrated for people living in Montreal, Canada [50], and in other countries. The differences between males and females cannot be explained in terms of occupational health hazards [27] and are usually attributed to differences in lifestyle.

Ratio of Health Benefits and Costs of Energy Development

As indicated above (Figure 1), the major health benefit of recent technological development is an increase of 35–40 years in average life expectancy. Many factors contribute to this increase, notably adequate nutrition, safe water supplies, adequate housing, improved medical care, etc. It is difficult to separate out the contribution of any single factor in a complex industrial society to the increase in life expectancy. An

Table 6: Health Benefits and Detriments of Technological Development and Energy Production in Terms of Life Expectancy (LE)

	Effect per kW per capita	*Reference*
Health Benefit		
Increase in LE due to technological development as total energy production increased from 2 to 6 kW per capita	6 years	Figs 1, 6, & 7
(Potential increase in LE attributable to commercial energy production in above range)	(0.6 years)	(see text)
Increase in LE as total energy production increased above 6 kW per capita	0.8 years	Figs 7 & 8
(Potential increase in LE attributable to commercial energy production above 6 kW per capita)	(0.08 years)	(see text)
Health Detriment		
Total risk of fatalities for safer sources of commercial energy production such as nuclear power and natural gas	$0.2\text{–}1 \times 10^{-6}$ deaths per year	Tables 3–5
(Potential loss of LE attributable to safer sources of energy production)	(0.0005–0.002 years)	(see text)
Total risk of fatalities for more hazardous sources of commercial energy production such as oil, coal, and wood	$10\text{–}20 \times 10^{-6}$ deaths per year	Tables 3–5 and text
(Potential loss of LE attributable to more hazardous sources of energy production)	(0.02–0.04 years)	(see text)

analysis of the variations in average life expectancy among different countries and within given countries over a 25-year period from 1950 to 1975 (Figure 6), indicated consistent correlations only with energy consumption per person (an indicator of industrial development) and with literacy of the population [35, 36]. On the basis of this type of analysis, the proportion of the total increase in life expectancy that might be directly attributed to energy production has been taken to be about 10% [35]. The cost of energy in all forms delivered to the end-using device is also about 10% of the gross domestic product [41]. This value of 10% will be used as a working hypothesis for calculation of cost-benefit ratios in terms of life expectancy, even though it is obvious that life expectancy depends upon many other factors in a complex social system, and that the industrialized social systems that have led to marked increases in life expectancy cannot function in the absence of energy sources.

Assuming, then, that the observed increase of 35 years in life expectancy in industrialized countries (Figure 1) is achieved by the time that the required commercial energy production has reached 2–6 kW per person, or total energy production has reached 4–6 kW per person (Figures 6 and 7), and that 10% of this increase could be assigned to energy production, the total health benefit in the earlier stages of industrialization would thus be approximately 0.6 years increase in life expectancy per kW per person (Table 6). More recent increases in life expectancy in Canada have been considerably smaller per unit energy consumed (Figure 7); assuming again that 10% is assigned to energy production, the health benefit would appear to be about 0.08 years increase in life expectancy per kW per person (Table 6).

The health costs of energy production can be calculated in the same units (i.e., years of life expectancy per kW energy consumed per person) from data on the statistical probability of a premature death per kW·a of energy produced (Tables 3–5). For this purpose, it is assumed that each premature death would result in an individual loss of about 30 years in life expectancy. (This value is a composite of estimated individual losses of about 10–15 years for fatal cancers induced by occupational exposure to radiation, combustion products, and other cancer-causing agents; about 20–30 years for exposures of the public to the same agents; and about 35 years for fatal accidents, either to workers or the general public.) It is further assumed that energy consumption will continue at the same rate for a lifetime of 75 years. The average loss life expectancy per KW per person is thus in the region of 0.001

Table 7: Benefit/Cost Ratios for Effects of Energy Production on Life Expectancy (LE), Assuming 10% of Health Benefits of Technological Development Could be Attributed to Energy Production
(data derived from Table 6)

	Increase in LE / Loss of LE	
	Developing countries	*Industrialized countries*
Safer sources	300–1000	30–160
More hazardous sources	15–30	2–4

years for safer sources of commercial energy, such as nuclear power and natural gas, or of 0.02 years for more hazardous sources, such as coal-fired power stations (Table 6). The benefit: cost ratios for energy production in terms of life expectancy would thus appear to be high, and are still much greater than 1.0 even in the industrialized nations of North America, which have currently reached higher levels of energy consumption per person than any other country in the world (Table 7).

The average health detriment associated with commercial energy production is not uniformly distributed in the population but falls selectively upon certain groups of workers, notably those involved in underground mining of coal and uranium, in logging and in offshore exploration for gas and oil. This topic has been considered in more detail elsewhere [27] and is summarized briefly in Table 8 for countries, such as Canada, that utilize about 10 kW per person from a

Table 8: Effects of Technological Development and of Various Aspects of Nuclear Energy on Life Expectancy

	Change in life expectancy in years
Shared benefit of technological development	+35
Shared detriment of production of 10 kW from mixed energy sources	−0.1
Specific detriments:	
(a) occupational fatalities in safe industries	<−0.15
(b) average occupational fatalities for all workers in Canada	−0.15
(c) occupational fatalities for workers in CANDU stations in Ontario	−0.05
(d) radiation-induced fatalities for members of public living on boundary of a CANDU site	−0.0014
(e) radiation-induced fatalities for members of public living within 30 km of Chernobyl site 26 Apr.–5 May 1986	−0.05

(a–c) Assuming a working lifetime of 50 years at recent levels of occupational fatalities or radiation exposures.

(d) Assuming an incremental exposure of 0.05 mSv per year for 75 years.

Table 9: Deaths of Persons Age 20–64 in Canada, 1983 (Statistics Canada 1985)

Cause	*Total deaths* (a)	*% of total*	
Pneumonia, influenza and tuberculosis	610	1.3	
Lung cancer	4507	9.5	42.3
Other cancer	15611	32.8	
External violent causes:			
occupational	782 (b)	1.6	18.6
motor vehicle (non-occupational)	2584	5.4	
suicide	2966	6.2	
other	2515	5.3	
Cardiovascular diseases	15124	31.8	
All other causes	2812	5.9	
Total	47511	100.	

(a) The values given are not standardized for age distribution of the population.
(b) Data from 1980 (Labour Canada 1982). An additional 89 deaths were attributed to occupational diseases.

mixture of energy sources. In contrast to underground uranium miners, workers in nuclear power generating stations do not suffer from a relatively high rate of fatal occupational accidents [12]. Average occupational exposures of these workers to ionizing radiation [12] are also low enough to bring the predicted rates of radiation-induced fatal cancers well below the limit of occupational fatalities in other safe industries. About 80% of all workers in Canada are employed in safe industries where the probability of an occupational fatality does not exceed one per 10,000 workers per year [21, 27]. For workers in nuclear power generating stations as well as for workers in other safe industries, therefore, the probability of a premature death due to occupational circumstances does not exceed one-fiftieth of the probability of death due to all other causes between ages 18 and 65 (Table 9).

For the type of calculations given in Tables 3 to 6, the predicted health hazards of releases of cancer-causing materials from current energy production facilities are usually summed over periods of about 100 years into the future. A complete cost-benefit analysis on the health effects of current commercial energy production and technological development might be considered to require a summation of all health benefits extrapolated over all future generations, and of all health detriments extrapolated over all future generations. No reliable analysis of this kind can be carried out at present. Improvements in technology and health care during the past 100 years have been so dramatic that any attempts to extrapolate the future health costs and health benefits of current activities to times much greater than 100 years into the future are extremely unreliable.

Discussion

There has in recent years been appreciable discussion on the advisability of further development of various energy sources. Some of these discussions have centred on associated health risks and on issues such as voluntary versus involuntary hazards [38, 39]. From the perspective of general health of the public and of workers, a more balanced discussion would attempt to examine both the health benefits and health risks of energy production and would include the involuntary health hazards associated with poverty and lack of technological development. Data pertaining to this topic have been presented above. The general conclusion from these data is that industrialization and technological development have proven to be remarkably effective in improving public health. The health benefits vastly outweigh any health detriments associated with the required energy production.

Many other factors (for example, relative costs, security of future supplies of raw materials, long-term effects of acid rain, and long-term effects of atmospheric accumulation of carbon dioxide) must be considered in societal efforts to make rational choices concerning further development of various energy sources. In general, most of these factors would appear to favour nuclear power as one of the major sources of electrical power in the future.

Any consideration of the health effects of energy development would be incomplete without some consideration of the effects of the catastrophic accident at the Chernobyl nuclear power site in the Ukraine in April 1986. The health effects of the Chernobyl accident have been discussed in detail [16]. It has been reported that 31 of the workers and firefighters at the site died as a result of the skin burns, trauma, and high radiation doses received on 26 April 1986; another 170 workers received radiation doses high enough to cause temporary, non-fatal symptoms of radiation sickness [16]. The number of immediate, known deaths attributable to this accident is small compared with potential effects on the general public of radionuclides released into the biosphere. About 135,000 members of the general public were evacuated from a 30 km zone around the Chernobyl site within 10 days of the accident; the increase in radiation dose received by these persons is currently estimated to average about 0.14 Sv [16], or roughly the same dose that people normally receive from natural sources over a 70-year lifetime. On the basis of internationally accepted standards, about 200 additional fatal cancers might be anticipated in this group of 135,000 persons within several decades; the resulting average decrease in life expectancy for these persons would be about 0.05 years (Table 8). There is still considerable uncertainty concerning the average increase in radiation dose to persons living in the Ukraine and other parts of western Russia outside the 30 km zone; current estimates suggest that the average increment in effective dose equivalent summed over the next 50–70 years would be somewhere in the region of 0.01 Sv per person [16]. The effects of 0.01 Sv on mortality of the general population of western Russia are summarized in Table 10. At this dose, the predicted number of additional fatal cancers among 75 million persons would be about 10,000 (with a two-fold range of uncertainty) and the average loss of life expectancy for the whole population would be about 0.005 years or 2 days, assuming 20–30 years loss of life expectancy per radiation-induced fatal cancer. This value, while not insignificant, is small in comparison to the health benefits associated with technological development and energy production (Figure 1 and Table 6).

Table 10: Predicted effect of radionuclides from the Chernobyl accident on the mortality of 75 million inhabitants of the Ukraine and western Russia (IAEA 1986)

Cause of death	*Expected before Chernobyl*	*Expected after Chernobyl*	*Difference*
Cancer	9.5 million	9.51 million	+ 10 thousand
Other causes	65.5 million	65.49 million	− 10 thousand
Total	75 million	75 million	0

In this respect, several additional items might be noted. First, the Chernobyl power station was not designed to the same standards of safety as, for example, the CANDU system [34, 44]. Second, the normal variation in exposure to radiation from natural sources in different Canadian cities is considerably larger, approximately 0.1 Sv over 70 years, due mainly to differences in the average concentrations of radon daughters in houses [46]. No significant differences in cancer mortality attributable to variations in radiation doses from natural sources in different Canadian cities have been observed. Third, current vital statistics for the USSR suggest that about 13% of all deaths are due to cancer [16, 48; see Table 10]; these statistics are similar to those which were applicable in Canada about 40 years ago (Figure 3). And finally, the health effects of the Chernobyl accident decrease with increasing distance from the site of this release of radioactive materials into the biosphere. The predicted number of fatal cancers induced in the Canadian population as a result of miniscule increments in radiation exposure caused by the Chernobyl accident appears to be less than one [31]. Although the Department of National Health and Welfare in Canada did recommend a temporary ban on drinking rain-water, due to detectable increases in radioactive iodines in May 1986, the limit on which this recommendation was based [15] is roughly 100 times smaller than the limits recommended by most other organizations concerned with emergency planning [17].

Radionuclides released into the biosphere as a result of the Chernobyl disaster are thus not expected to have significant adverse effects on the health of people in any country, including the USSR (Table 10). Assessments of the safety of nuclear reactors with North American standards for secondary protective features including containment are currently being re-examined. There does not as yet appear to be any reason to alter the conclusion that nuclear power produces fewer adverse health effects than most other sources of energy in western countries (Tables 3–5), and that the average health benefits associated with technological development and industrial prosperity outweigh any health detriments of the required energy production by a very large factor (Tables 6–8).

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