Sanitary energy costs

Roland Masse (roland.masse2@wanadoo.fr)
Académie des technologies, 19 rue Leblanc, 75015 Paris

Energy production and consumption are essential to the development of industrial societies. It has been shown that there is a strong correlation between the increase in life expectancy and the amount of energy per capita, but that this effect reaches a plateau at a value of less than a quarter of that of current Western societies.
In addition to energy consumption, the interaction between energy and health is dominated by the effects of environmental pollution.

The health impact of energy production and consumption makes a decisive contribution to the external cost of energy i.e. the price paid not by energy market players but by society as a whole.

In the 2014 European analysis, "Subsidies and costs of EU energy" (which updates the ExternE study launched in the 1990s), the monetary evaluation of the health impact of deployed energy is ranked third, after climate change and resource depletion.

Identifying risks

The identification of health damage attributable to energy must take into account the entire life cycle of each sector and each of its components. In both accidental and normal operating situations, this includes the impacts of extraction, processing, production, transport and waste.

Impact of accidents

Early impacts

The consequences of accidents, the most serious of which are well known, were reviewed in 2014 by the Paul Scherrer Institute and now cover the period 1970-2018 [1]. They are summarised in Table 1.

More than 200 people were evacuated as a result of: 65 oil accidents,

	OECD countries			Hors OCDE		
Energy sectors	Accidents	Number of deaths	Number of death/ GWe.an (*)	Accidents	Number of deaths	Number of deaths/ GWe.year (*)
Coal	87	2 259	0.157	2 394	38 672	0.597
China 1994-1999				818	11 302	6.169
China 1999-2008				1 214	15 750	
China excluded				162	5 788	
Oil	187	3 495	0.132	358	19 516	0.897
Natural gas	109	1258	0.085	78	1 556	0.111
GPL	58	1856	1.957	70	2 789	14.896
Hydro	1	14	0.003	21	30 069	10.285
Nuclear	0 (**)	0	0	1	31	0.048
Biofuel	0	0	0	0	0	
Biogas	0	0	0	2	18	
Geothermal	0	0	0	1	21	
Total	**442**	**8 882**		**2 925**	**92 672**	

Table 1. **Number of severe accidents involving early death directly attributable to the energy sectors : coal, oil, natural gas, liquefied petroleum gas (LPG), hydroelectricity, nuclear.** Severe accidents are those involving one of the following criteria: at least 5 fatalities, or at least 200 evacuees, or a ban on the consumption of local products, or the release of more than 10,000 tonnes of hydrocarbons, etc.
(*) In this table, the units in GWe.year (i.e. 8.76 TWh) all refer to energy produced and not to energy consumed.
(**) The two serious nuclear accidents at Three Mile Island and Fukushima did not result in any early deaths attributable to nuclear energy

Article available on website https://www.refletsdelaphysique.fr or https://doi.org/10.1051/refdp/2024s162

The Courrières coal mine disaster (Pas-de-Calais), illustrated by *Le Petit Journal*. This disaster, caused by an explosion of highly flammable carbon dust on 10 March 1906, officially claimed 1 099 lives.

28 LPG (liquefied petroleum gas) accidents, 18 natural gas accidents, 3 dam accidents, 3 nuclear accidents. The total number of evacuees affected more than 1 500 000 residents. The largest evacuations were for LPG: 220 000 evacuated in 1979 in Missisauga (Canada) and 200 000 in 1984 in Mexico City; for hydroelectricity: 150 000 evacuated in 1979 in Moravi, India; for nuclear 144 000 evacuated in 1979 in the USA (Three Mile Island), 135 000 in 1986 in Ukraine (Chernobyl) and 160 000 in Japan in 2011 (Fukushima); for oil: 100 000 evacuated in 1988 in Mexico City.

Accidents occurrence : in the case of coal, 96% during mining; in the case of oil, 76% during transport and storage, 15% during drilling and 8% during refining; in the case of natural gas, 78% during transport and storage, 6% during drilling and 5% during production, in the case of nuclear power during production entirely. Some data are available on accidents in the photovoltaic sector, depending on the techniques used. They concern around a hundred deaths, giving a normalised rate of around 10^{-3} per GW per year; to this must be added deaths attributable to the installation of panels on roofs, for which there is no overall assessment. There is no comprehensive database on accidentology in the wind energy sector; despite various material accidents, human accidents are rare. The most complete inventory appears in the proceedings of the Caithness Windfarm forum 2017, and concerns 2057 accidents and 130 deaths worldwide; but, according to the authors, the statistics may only cover less than 10% of actual accidents.

Late impacts

Late deaths, attributable to toxic derivatives of petroleum products and biomass released into the environment by the accidents, are conceivable but are not counted.

In the case of nuclear power, late deaths due to radiation-induced cancers[a] account for most of the detriment attributable to accidents. With the exception of thyroid cancer in children, for which an excess of more than 6 000 cases was observed in areas contaminated by radioactive iodine after Chernobyl, epidemiology is currently unable to directly determine the impact of this accident on other cancers. Their number is assessed by modelling based on environmental exposure measurements and experience acquired in reference irradiated human groups, in particular the survivors of Hiroshima and Nagasaki. However, for exposures below 100 mSv[b], there is no data to show that a risk exists in proportion to the dose received; as a precaution, it is accepted that it is not currently possible to exclude the existence of such a risk.

Depending on whether we consider that this assumption applies to all populations worldwide, however low the doses received, or whether we wish to restrict the calculation to populations whose committed doses are no more than an order of magnitude lower than 100 mSv, the count of attributable deaths varies significantly. In the Paul Scherrer Institute's calculation, for example, the proposed range is between 9 000 and 33 000 deaths, most of which occurred at the end of life, all attributable to the Chernobyl accident. On the same assumption, the Three Mile Island accident would result in one attributable death, and 600 deaths would be expected after Fukushima.

Other causes of mortality need to be considered. For professionals exposed to more than 150 mSv, such as the Chernobyl liquidators, an excess of mortality attributable to

>>>

© Tim Porter (Wikimedia Commons, 4.0 International)

1. The containment shell of the damaged No. 4 reactor at the Chernobyl nuclear power plant in Ukraine and its first sarcophagus, due to come into service in 2019. 108 m high, 162 m wide and with a span of 257 m, it is designed to last 100 years.

>>>

radioinduced cardiovascular effects is recorded, in a proportion comparable to that for cancers. These effects only appear above a dose threshold that is higher than most accidental environmental exposures.

In addition to the direct effects of radiation, the indirect effects of post-accident crisis management must also be taken into account, particularly those resulting from the long-term evacuation of the area: around 115,000 residents in the Chernobyl area and 160 000 in the Fukushima area.

This component has a health cost, but it is difficult to assess. It may, however, far exceed the cost of the health effects directly caused by the accident itself. In the case of the Fukushima accident, which caused no casualties through exposure to ionising radiation, the displacement of the population and their rehousing in makeshift conditions led the Japanese authorities to recognise around 2,000 attributable premature deaths. This impact should be assessed in situations where there is a deterioration in the living environment associated with extractive industries in normal or degraded operation (Bayan Obo in Inner Mongolia for rare earths, Alberta in Canada for oil sands extraction, Garzweiler in Germany for lignite, the Appalachians in the United States for coal, etc.), or in the case of population displacement for the impoundment of large dams (Three Gorges Dam in China: 1.8 million people displaced according to *Wikipedia*).

Health impact in normal operation

Nuclear energy

In normal operation, as in accident situations, the risk factor is external or internal overexposure to ionising radiation for professionals and the public.

Exposure is assessed by measurement and modelling. For workers, with the exception of uranium miners exposed to radon, most of the accumulated doses come from external exposure measured on an individual or collective basis; for the public, most of the exposure is due to the release of various radionuclides into the environment, and the dose is assessed by modelling their transfer into the air, water and food chain.

For the entire nuclear cycle in France in 2003, the calculated balance over a period of 100 000 years was 13.1 men. Sv/TWh [2]; this balance is constantly decreasing under the pressure of radio protection measures. Applying this model to all the world's nuclear production and distributing all the doses over the world's population gives an estimate of 2.5 microsieverts per person per year. At such a dose level, 1000 times lower than that corresponding to natural radioactivity, the health impact, if it exists, can only be inapparent.

Occupationally exposed groups do, however, constitute a group where the health impact of exposure to ionising radiation is detectable. This is the case for uranium miners exposed to radon. More than 10 000 of them have died of lung cancer since 1946, including more than 7 000 in the former GDR, most of them exposed to extremely high levels. In France, 211 miners have died of lung cancer out of 5 000 exposed miners, with around 60 attributable to exposure. In the case of other nuclear workers, epidemiological studies show a lower incidence of cancer than in the general population. Assuming a linear dose-effect relationship with no threshold, an excess of 300 cancers is conceivable among the 75 000 expected.

Carbon-based energy

Coal extraction

Apart from accidents, coal mining is the cause of occupational diseases due to dust inhalation: pneumoconiosis-silicosis and lung cancer. The current average number of annual deaths from coal miner's pneumoconiosis is 0.4 per 100 000 inhabitants worldwide, including around 80 in Germany and 140 in the UK. The prevalence of pneumoconiosis-silicosis in China currently involves more than 500,000 miners, with the number of new cases probably exceeding 20,000 per year, and several thousand fatal accidents.

Health impact of CO_2

The production of CO_2 is the risk factor common to all carbon-based energies and makes a decisive contribution to global warming. Since

	NO_x Grams per GJ	COVNM Grams per GJ	PM10 Grams per GJ	PM2,5 Grams per GJ
Coal-Lignite	95-200	1.2-20	47	28
Wood	200	4.8	77.5	61
Heavy fuel oils	170-190	3	20.4	8.4
Heating oil	100	2	4.1	1.7
Other petroleum products	170	3	20.4	8.4
Natural gas and other	42-75	1.5-2.5	0.9	0.9

Table 2. **Standardised emissions of nitrogen oxides (NOx), non-methane organic compounds (NMVOCs) and particulate matter less than 10 µm (PM10) or 2.5 µm (PM2.5), for different carbon energy sources.**

1850, the resulting heat waves in France have been responsible for more than 20000 premature deaths [3]. Lastly, climate change is already having an impact on changes in the distribution of harmful plant species, some of which are the cause of severe allergies (e.g., ragweed), and on the proliferation of vectors of tropical diseases such as dengue fever, chikungunya and zika in temperate countries.

Toxic emissions

The combustion of carbonaceous materials releases toxic emissions into the atmosphere.

Emissions of particulate : variously described as black smoke, total suspended particulates (TSP), PM10 and PM2.5 (particles smaller than 10 or 2.5 µm in diameter) and soot carbon (BC).

Gaseous emissions: carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds other than methane (NMVOCs), in particular those responsible for the formation of ozone (O_3) by photochemical reaction.

SO_2 and NO_2 oxides are also responsible for a large contingent of atmospheric particles through the nucleation of sulphates and nitrates after reaction with NH_3 ions of mainly rural origin. These secondary particles can account for up to 80% of the mass of PM2.5 in atmospheric aerosol and act as a carrier for toxic volatile components of the primary emission.

Several constituents of the gaseous and particulate phase are potentially dangerous, particularly **neurotoxic** due to mercury and lead, and **carcinogenic** due to certain *metals* (As, Cd, Ni, Cr) and several *organic compounds*: polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/F), hexachlorobenzene (HCB).

The different energy sources have very different emission levels, as shown in table 2 from the Citepa Ominea 92 report. Changes between 1990 and 2020 in the contribution made by the various energy sources to emissions of various toxic substances into the environment in France have been reported in regularly published data by Citepa [4].

The health impact of air pollution

It is not possible to assess directly the health impact of each of the toxic constituents emitted into the atmosphere by carbon-based energy sources. However, we do know quite a lot about what happens when the whole mixture is inhaled.

Broadly speaking, two types of study are being carried out: (1) those which establish daily temporal correlations between variations in the concentration of pollution indicators and simultaneous variations in health indicators; (2) those which analyse the long-term consequences of exposure to atmospheric pollutants on stable cohorts monitored for decades.

For short-term effects, a summary of the data acquired was proposed in 2011 [5]: an increase in atmospheric particles of 10 to 20 mg/m^3 of air is correlated with a 0.4 to 1.5% increase in mortality.

Different atmospheric pollution indicators, such as those used in the 2002 INVS PSAS-9 report (table 3), give globally consistent results, essentially reflecting the tracer nature of these indicators and not their toxicity (the effects do not add up).

The indicator most commonly used for long-term type 2 studies is PM2.5, which is correlated with excess mortality: all causes, cardiopulmonary, cardiovascular and ischaemic heart disease. The validity of these correlations has been confirmed by the development of policies to reduce exposure, which have had a direct impact on reducing mortality and morbidity rates [6].

For all-cause mortality, an essential indicator of the impact on health, the average attributable risk for an

>>>

	Taking into account air pollution on the day of death and :	Black smoke	SO_2	NO_2	O_3
Total mortality	- the day before	0.8 %	1.1 %	1.0 %	0.7 %
	- of the previous five days	1.2 %	1.9 %	1.3 %	nd
cardiovascular mortality	- the day before	0.5 %	0.8 %	1.2 %	1.1 %
	- of the previous five days	1.2 %	1.7 %	1.4 %	nd
Respiratory mortality	- the day before	0.7 %	1.1 %	1.3 %	1.2 %
	- of the previous five days	2.1 %	5.1 %	3.4 %	nd

Table 3. **Excess mortality risk (percentage) for a 10 mg/m^3 increase in pollutant levels.**

>>>

increment of 10 mg/m^3 is of the order of 7 to 14% of excess mortality. These values are behind the WHO's annual estimates of 7 million deaths worldwide in 2014 and 48 000 deaths in France, given current levels of air pollution. The vast majority of attributable deaths are therefore due to the delayed effects of background pollution, and not to pollution peaks. They occur at the current levels observed in France (10 to 15 mg/m^3 for PM2.5).

The relative share of pathologies specifically associated with air pollution is the subject of variable assessments for the three main ones: pulmonary, cardiac and vascular, and lung cancer. For cancer, a central value is around 9% of new cases of lung cancer per 10 µg of PM2.5 or PM10; but this value can be as high as 22% for urban populations in Europe.

Specific toxic effects identified

Certain components of atmospheric pollution: CO_2 under accidental conditions, SO_2 associated with the great *smogs* (see photo p. 142) and ozone - unquestionably have their effects.

Concentrations of nitrogen oxides are below the levels associated with identifiable toxic effects, but there are strong correlations between atmospheric NO_2 levels and cardiopulmonary mortality.

The inhalation of atmospheric particles from urban aerosols is associated with multiple effects that depend on the territory of particulate deposition in the airways. The PM10 fraction is associated with bronchial irritation; the PM2.5 fraction is associated with vascular cell damage; and the ultrafine component escapes local sequestration and migrates via the bloodstream to various organs. The most consistent toxic mechanism is the induction of oxidative stress.

It is not possible to distinguish whether the vascular toxic effect of PM2.5 is physical in nature or associated with adsorbed mineral and organic toxicants. There is a consensus that natural particles from sea spray and erosion are not involved, whereas carbon-rich particles systematically are. There is some debate about the role attributed to sulphate and nitrate particles.

The assessment of systemic effects, possibly due to the impact of neurotoxins, carcinogens and mutagens emitted into the environment during the combustion of carbon sources, is assessed indirectly from modelling.

Assumptions used to assess the health consequences of different sources of carbon-based energy

Most of the health impact is associated with matter particles, expressed as PM10 for acute effects and PM2.5 for chemical effects. The acute effects of ozone, which can be distinguished from those of particulate matter, are added, and the systemic effects of metals and toxic organic compounds are taken into account, although this has little effect on the overall impact.

From this perspective, SO_2 and NO_x molecules are only taken into account for their impact on health as sources of particulate matter.

There is little change in primary aerosols at distances of less than 50 km from the emission source, and their modelling in the ExternE study [7] is based on a simple Gaussian straight-line propagation model. However, at greater distances, chemical reactions take place in the atmosphere, leading to the formation of secondary pollutants - ozone, sulphates and nitrates. Their behaviour is modelled using more complex Lagrangian models.

Health balance of carbon-based energy

In most cases, indicators of health damage are expressed as relative risk (RR), which is the ratio of the number of cases observed after exposure to an excess concentration of the toxicant in question to the number of cases existing without this excess exposure.

The relationship between mortality and PM2.5 concentration in Europe can be described [6] by a simple linear log function:

$\Delta y = y_0[1 - \exp(-\beta\Delta x)]$,

where Δy is the reduction in the number of deaths that would be associated with a reduction Δx in the PM2.5 concentration; β is the slope of the relationship between the logarithm of mortality and the PM2.5 concentration; in the case of a relative risk RR, observed for exposure to 10 mg/m^3, the value is $\beta = \ln(RR/10)$.

The ExternE study uses a simplified expression relating PM2.5 concentration proportionally to the loss of years of life, over the range of usual exposures. This property, despite the non-linear determinants that condition it, makes it possible to define a generic value for Europe of 0.22 days of life lost per 1-year exposure to an excess of 1 µg/m^3.

A summary has been proposed for the whole of Europe subject to the fallout from carbon-based energy production (table 4). For a total of 2.2 million years lost, with a loss per case estimated at five years, these figures correspond to around 450 000 premature deaths for 1998.

1• P. Burgher et S. Hirschberg, “Comparative risk assessment of severe accidents in the energy sector”, *Energy Policy*, **74** (2014) S45-S56.

2• *Électricité nucléaire : Quels sont les couts externes ?*, Rapport NEA 4373, OCDE (2003).

3• M. Pascale *et al.*, « Changement climatique et santé », *Bulletin Épidémiologique Hebdomadaire* **38-39** (2015) 718.

4• Citepa, *Gaz à effet de serre et polluants atmosphériques. Bilan des émissions en France de 1990 à 2022*, Rapport Secten éd. 2023.

5• C.A. Pope, “Health effects of particulate matter air pollution”, EPA wood smoke webinar (July 28, 2011).

6• M. Pascal *et al.*, « Impacts de l’exposition chronique aux particules fines sur la mortalité en France continentale et analyse des gains de santé de plusieurs scenarios de réduction de la pollution atmosphérique », Santé publique France (2016).

7• ExternE-Pol Final technical Report, Rabl A Spandaro J coordinators, 2nd version Aug 2005

8• *New Elements for the Assessment of External Costs from Energy Technologies*. R. Friedrich (coordinator), Final Report to the European Commission (Septembre 2004).

9• A. Rabl et J. Spandaro, « Les coûts externes de l’électricité », *Revue de l’énergie*, **525** (2001) 151.

10• N. Starfelt et C.E. Wikdahl, Energy forum, “Economic analysis of various options in electricity generation - Taking into account health and environmental effects”, Proceedings of Ecological Aspects of Electric Power Generation, Warsaw (Nov 14, 2001)

11• A. Markandya et P. Wilkinson, “Electricity Generation and Health”, *The Lancet*, **370** (2007) 979.

Health effects of other energy sources

Apart from accidental situations, most of the health effects associated with other types of energy result from the use of carbon-based energies over the course of a lifetime.

The key feature of the wind and photovoltaic industries is the health risk posed by the heavy metals required for their use.

Standardisation and comparison of electricity generation risks

The results of the European and American summaries were used to rank the technologies according to the damage attributed per TWh. The result for Europe, expressed in years of life lost [9], is shown in Table 5.

The same work, carried out in Sweden [10] and the UK [11], counts the premature deaths specific to emissions in these countries: tables 6 and 7 .

Forbes magazine also published an assessment in 2012 which, in terms of premature deaths, attributed per TWh of electricity produced in the United States : 15 to coal, 36 to oil, 4 to gas, 24 to biomass, 0.4 to solar, 0.15 to wind, 1.4 to hydro and 0.09 to nuclear. These figures are comparable to those from the ExternE study within a factor of 2, with a few exceptions.

In terms of health effects, the choice of energy mixes has a major impact on overall impacts. A comparison of the expected impacts of electricity generation in 2015 suggests that : in France (546 TWh) 7,300 life-years lost and 460 premature deaths, and in Germany (647 TWh) 41,300 life-years lost and 8,400 premature deaths.

Conclusion

The general hierarchy of health costs for the different energy production sectors is very clear, as the cost of carbon-based energies is disproportionately high compared with other sectors. This cost suggests that there will be around 100 million premature deaths worldwide, for a lifetime of exposure. The cost is very high and has a significant impact on the cost of non-carbon energies upstream and downstream of their production, particularly during the intermittent nature of renewable energies.

Whatever the way in which the damage is expressed, taking into account accidental situations and normal operation, the health toll paid by professionals and that suffered by the public, coal and oil, which are responsible for hundreds of thousands of deaths per year in Europe, are far ahead of the other sectors. Nuclear power and renewable energies are the best performers in this field, while gas and biomass have an intermediate level of nuisance. ▮

This article is a reduced version of the original article "The health cost of energy" by Roland Masse (revised version dated 19 March 2023), which appeared on the website of the association Sauvons le climat (www.sauvonsle-climat.org).

	All emissions N years lost	Power stations N years lost
In Europe	2 070 000	420 000
Outside Europe	170 000	70 000

4. Mortality attribuable to carbon-based energy in Europe in 1998 according to the study ExternE [8].

Coal	Oil	Gas	Nuclear	Biomass	Wind	PV
122	150	32	9	77	6	12

Table 5. Losses in years of life per TWh after 2000, according to different energy sources in Europe **.**

Coal	Lignite	Oil	Gas	Nuclear	Biomass	Hydro	Wind
25	18	37	4	1	12	< 1	> 1

Table 6. Number of premature deaths* attributed in Sweden per TWh according to differentenergy sources. (*ExternE considers an average of five years lost per premature death).

Coal	Lignite	Oil	Biomass	Gas	Nuclear
24.5	32.6	18.4	4.6	2.8	0.05

Table 7. Number of premature deaths by disease in the United Kingdom, per TWh and according to different energy sources.

(a) A 0.2% per sievert risk of inducing transmissible genetic diseases has been added to the exposure liability, even though no epidemiological data has established the existence of such diseases.

(b) The risk indicator used to describe the late effects of ionising radiation, particularly carcinogenic effects, is the sievert (Sv). It is a unit of dose, weighted to allow dose additivity. It is derived from the gray (worth 1 joule/kg) by two weighting factors, one specific to the radiation and varying from 1 to 20, the other, less than 1, specific to the tissues and organs concerned.