Working Paper 1993:8

Sources of energy and the environment[1]

by

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[1] This working paper is based on the manuscript for chapter three in the forthcoming volume "Global Oil Markets", edited by Siamack Shojai and published by Praeger Publishers.

1. Introduction

Of all human activities the extraction, conversion and consumption of energy are among those having most influence over the environment. The influence can be in terms of pollution of air and water, solid waste, global warming, and land depreciation, etc. Associated with these environmental influences are consequences in terms of public health effects and increased corrosion of infrastructure, buildings and works of art, and a possible reduced productivity in agriculture and forestry. The environmental effects depend on energy extraction, conversion efficiency, energy end use, fuel mix, and on the level of emission mitigation. There is some uncertainty associated with the physical and biological effects of energy production and use due to insufficient knowledge, natural variations, potential synergistic effects, and potential threshold contamination levels. For some energy production activities, like nuclear power production, there is some risk of accidents of extensive and serious consequences.

Next we will briefly consider the most important energy sources, their fuel cycle from production to end use, and the major factors determining the total environmental impact. In the main part of the paper the environmental impacts in terms of emissions of pollutants and other effects of each energy source are discussed with reference to the final section containing a classification of environmental impacts divided into local impacts, acid deposits, and climate change. Priority is given to the description of various energy sources and their environmental impacts, whereas the treatment of mitigation options like energy efficiency improvement and environmental control technologies is cut short.

2. Energy sources, fuel cycles, and total environmental impact

Energy sources can be divided into exhaustible and renewable energy sources. The exhaustible energy sources are the fossil fuels oil, coal and natural gas, and the nuclear energy source uranium. The renewable energy sources are based on solar energy, on geothermal energy, or on gravitation energy (i.e. tidal power). The solar energy sources are hydroelectric, wind power, photovoltaic power, solar thermal, solar heating, biomass, and solar energy derived from the ocean, where the most important forms are wave energy and ocean thermal energy (i.a. heat pumps).

For each energy source there is a fuel cycle from exploration, to extraction, to conversion (e.g. electricity generation and oil refining), to transportation and distribution of energy, and to energy end use and consumption in sectors such as industry, transport and buildings. To supply a given net use of energy the necessary primary extraction depends on the efficiency for each of these fuel cycle steps. The lower the efficiency the more waste heat or unused material is released. Each fuel cycle step has some environmental impact through emissions and other influences. Some of the environmental impacts can be mitigated. Thus the total environmental impact from energy use depends on:

i) What and how much is produced, and where it is produced.

ii) How are goods and services produced.

iii) How much of the impacts are mitigated.

The first item refers to the economic structure in terms of the goods and services produced. There are different environmental impacts associated with different goods and services due to different production and consumption technologies and patterns, specifically with respect to energy requirements. The geographical distribution of production and consumption is of importance for the local environmental impacts.

Since the total environmental impact to a large extent depends on primary energy extraction, the efficiency through the fuel cycle to end use is important. For a given energy end use a low efficiency means a higher primary energy production and thus a larger environmental impact. The fuel mix (i.e. share of different energy sources) is another vital factor since the environmental impact varies among different energy sources. A comprehensive study of the external costs of the coal fuel cycle has been initiated by the Commission of the European Community and the United States Department of Energy, see ETSU (1993) and Markandya and Rhodes (1992). The study will be expanded to include other main energy sources, including important renewables, and energy conservation.

The last item refers to mitigation of environmental effects through purification technologies and restoration activities like applying lime to lakes damaged by acid deposits. Some potential pollutants and waste materials can be recycled such that the environmental impact is reduced.

3. Environmental impacts of different energy sources

Environmental impacts of some energy source can be evaluated at three different levels. The first level relates to emissions of pollutants to water and air, solid waste, radiation (from nuclear power facilities), and waste heat. The next level relates to the biological and physical consequences of these influences in terms of reduced forest growth, damage to other vegetation cover, reduced fish populations in lakes due to acid deposits, public health hazards, corrosion of materials, global warming, and land depreciation, etc. At the third level the biological and physical consequences are evaluated and compared as part of the total consequences of different energy options, commonly by expressing everything in money terms. In this section the emissions, solid waste, radiation and physical impacts related to energy use will be considered, whereas the public health, biological, physical and climate consequences are discussed in the final section of the chapter. On the valuation of environmental quality and the problems related to this there is a large literature which can not be reviewed in the present context; see Cropper and Oates (1992) for a survey of contributions from economists.

3.1 Oil

The main environmental consequence from oil extraction is related to oil spills. The impact of oil spills depends on the oil quality, the volume and the speed of the spill (e.g. if there is a blowout from a production platform), and on the timing and location of the spill. In the case of offshore oil extraction fish populations and sea birds are in particular vulnerable, but the experience is that such impact is local and limited in time. Oil shale is a fine-grained sedimentary rock containing layers of organic material. Oil can be extracted through heating. This process gives rise to solid wastes, water contamination, air pollutants and fugitive dust, see Argonne National Laboratory (1990). The extraction of oil and oil shale may lead to land subsidence, dependent on the overburden composition and thickness and the extraction technique. The impact of oil spills from transportation (e.g. oil tankers) and distribution are comparable to oil spills from extraction activities.

In the process of oil refining the main emissions are sulfur oxides, carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons, and particulate matter. In addition there is some wastewater containing oil and water-soluble hydrocarbons.

The final step in the life cycle of oil is combustion for heat production, electricity generation in thermal power plants, or transformation to kinetic energy in engines and turbines in the industry and transport sectors. The main emissions related to combustion are carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, polynuclear aromatic hydrocarbons (PAH), and some heavy metals. These pollutants give rise to local impacts, in addition to acid deposits from sulfur oxides and nitrogen oxides, and global warming from carbon dioxide.

3.2 Coal

Coal is the most abundant fossil fuel at the global scale, and is available in different qualities from anthracite (high carbon content) via bituminous coal to lignite (low carbon content). Coal is extracted from underground mining or from surface mining. The quality of coal can be increased through a kind of refining process or preparation (i.e. "coal washing"). Coal is to a large extent transported on railroads and barges. There are some atmospheric emissions from diesel-powered mining equipment, thermal dryers, preparation activities, and transportation. These are primarily nitrogen oxides, sulfur compounds, hydrocarbons, and carbon dioxide, see Argonne National Laboratory (1990). Methane, other mine gases and coal dust can lead to explosions. Surface mining causes disruption of large areas and landscape changes, and release of fugitive dusts. Another consequence of coal mining is water quality degradation due to water drainage from mines, leaching and erosion of solid wastes, and modifications of aquifers. Underground mining may lead to land subsidence. Furthermore sites are needed for the solid waste disposal. These emissions can lead to dust problems and reduced visibility, damage to vegetation, and human health consequences (a review of environmental impact assessment for coal is given by Jones (1992)).

In a conventional coal-fired power plant electricity is generated through combustion of coal in a boiler which produce high-pressure steam that propels a turbine, which thereafter drives a generator. The thermal efficiency (the fraction of the energy converted to electricity) is typically 35% in most developed countries (WRI (1990)). During the combustion process particulate matter (solid and liquid) are emitted to the atmosphere together with sulfur dioxide, nitrogen oxide, carbon dioxide, carbon monoxide, PAH, and some heavy metals. Discharges to water are mainly associated with cooling water and ash handling. These emissions and thermal pollution can have significant impact on aquatic ecosystems. Systems for controlling emissions to air and water, and solid waste are auxiliary to a modern power plant. Sulfur dioxide can be removed through a stack scrubber where the gas reacts with limestone or lime to produce calcium sulfite or sulfate (Argonne National Laboratory (1990)). Through a second main desulfurization method sulfur is regenerated as a by-product and the reactant is recycled to the scrubber. Large amounts of ash and scrubber sludge can cause a waste disposal problem. The site size of a power plant in the 500 MWe is typically between 500 to 1000 acres (Argonne National Laboratory (1990)).

A newer coal technology is based on fluidized-bed combustion, where fuel burns in a bed of particles which are suspended and rapidly moved by an upward flow of air and combustion gases. Three advantages compared to a conventional boiler are higher thermal efficiency, removal of sulfur dioxide during combustion, and reduced level of nitrogen oxides. Coal gasification and coal liquefaction are alternative technologies. The products of the latter, however, are generally more toxic than crude oil and shale oil.

A higher overall thermal efficiency can be achieved through combined cycle power plants, up to 44% (WRI (1990)). Hot-combustion gas turbines and steam turbines are then combined to generate electricity. In addition to a lower primary energy use causing less emissions this technology allows emissions to be reduced compared to the conventional boiler technology. In cogeneration systems (i.e. combined heat and power systems) electricity is generated and direct heat provided for residential and commercial heating. The overall efficiency (electricity and heat) can be up to 85% (WRI (1990)).

Coal-burning magnetohydrodynamic (MHD) electricity generation is likely to be available in the future, where electric power is generated by passing an electrically conducting fluid (coal combustion products) through a magnetic field without any moving mechanical parts. The advantages of this technology would be higher thermal efficiency and less release of pollutants than conventional coal technologies (Kessler (1991)).

3.3 Natural gas

Gas leakages may occur during extraction activities and transport through pipelines or on LNG-ships. In the latter case the natural gas is liquid at a temperature of -161 °C. Extraction of gas may lead to land subsidence. Gas leakages are a fire hazard and in some concentrations there is a danger of explosion. Before the gas is distributed water, carbon dioxide, higher hydrocarbons and hydrogen sulfide are removed.

During combustion of natural gas the emissions are substantially smaller than for coal and oil. For nitrogen oxides the release to air is about half of that for coal and oil combustion (Pleym et al. (1992)). The emissions of carbon dioxide are about 60% of coal-related emissions and 70% of oil-related emissions.

In fuel cells electricity is generated from the chemical reaction of a fuel, such as natural gas or coal gas, and an oxidant, such as air or pure oxygen, see Schora and Cámara (1991) and Argonne National Laboratory (1990). This technology has many advantages compared to conventional fossil fuel electricity generation technologies. The energy efficiency is relatively high and level of emissions of nitrogen oxides, sulfur dioxide and particulates is low. One reason for the low emissions is the use of relatively clean fuels.

3.4 Nuclear energy

Most commercial power reactors producing electricity are light-water reactors (LWRs), which use ordinary water as heat-transfer medium and as a moderator for the nuclear reaction. The fuel is uranium, which is enriched to increase the concentration of the fissionable isotope uranium-235. There is some release of radioactive materials from uranium ore milling and enrichment facilities. The breeder reactor is an alternative nuclear technology where excess neutrons from the fission process are employed to convert a radioactive material to a fissile fuel and thus obtain a net production of fissile fuel. Fusion power plants may be available in the future, and are expected to be much safer than fission reactors.

Nuclear power plants produce radioactive isotopes, and small amounts of these are leaked during normal operation through the cooling system of the plant and as radioactive gases and particles through ventilation systems and control systems for radioactive waste. From the numerous fission products one is most concerned for the long-lived isotopes tritium, carbon-14, krypton-85, and iodine-129, which pose the largest public health hazard (Argonne National Laboratory (1990), Pleym et al. (1992)). The threat to human health is negligible under normal operation, but there is a small risk of major accidents of large consequences, as for example the Chernobyl accident of 1986.

The main types of radioactive waste are high-level waste (spent fuel and high-level waste from reprocessing), uranium mill tailings (sand and fine-grained material with low concentration of radioactive isotopes), and low-level waste (all other types of radioactive waste). Some of the high-level radioactive waste can be reprocessed but the rest require long-term storage. The release of radioactive materials from the reprocessing plants during normal operation is larger than from the power plants. Geologic repositories are considered to be the best alternative for permanent disposal. There is some risk of release of radioactive materials from accidents related to waste transport, handling and reprocessing.

3.5 Hydroelectric

Hydroelectric power plants are relatively clean in terms of environmental impacts, but they cause microclimatic, hydrological, biological, and landscape effects. Most of these effects are related to formation of artificial lakes (reservoirs) and resulting change in river flow and hydrological regime. Vegetation, fish populations and other species are negatively affected by the hydrological and climatic changes. The aesthetic value of the landscape may be reduced due to reservoirs and power lines. Furthermore, resettlement of local inhabitants may be required, and a risk of flooding of the downstream population arises due to the possibility of a collapse of reservoir walls. The environmental impacts are reduced for small-scale hydropower plants.

Transmission of electricity require high voltage lines, whether produced by hydropower, thermal power or nuclear power. Due to cost considerations these are commonly overhead transmission lines and not underground cables, confer Belmans and Geysen (1992). In Western Europe the highest voltage level is around 400 kV, whereas 750 kV lines are installed in North America. From present knowledge the electromagnetic field surrounding the lines does not appear to pose any health risk to people living nearby. However, some audible noise is generated by the lines.

3.6 Solar energy derived from the ocean

These technologies are not well developed today, but a few small scale pilot projects exist.

Wave energy is based on two main technologies for electricity generation, either wave focusing moving water into a reservoir at the shore, where the water flow back through a turbine, or buoys with swinging water columns pumping air through a turbine. The area requirements for wave energy plants are large, and there will be restrictions on ship traffic, fishing and other use. There will be some influence on fish populations, vegetation and marine life in general.

The future potential of Ocean Thermal Energy Conversion (OTEC) is probably large. The idea is to exploit the large temperature gradient which exists in much of the world's oceans. OTEC systems are only realistic in tropic waters since a temperature difference of at least 20 °C is needed. In a closed cycle system warm water is used to evaporate a suitable working fluid running a turbine, after which the fluid is recondensed in cold water. In the open cycle system the ocean water itself is used as working fluid, confer Fisher (1990). Full-scale OTEC plants could harm tropic biota, disrupt ocean currents and influence the climate. There could be harmful emissions of the working fluid. If chlorofluorocarbons are employed, emissions cause stratospheric ozone depletion and, because chlorofluorocarbons are greenhouse gases, increased global warming.

In a smaller scale ocean thermal energy is available close to the shore through heat pumps, employing a similar working fluid as in OTEC. The thermal energy is suitable for heating buildings. Other thermal energy sources for heat pumps are waste water, soil, underground water and the bedrock.

3.7 Wind energy

Wind energy is captured through a turbine design which convert the kinetic energy to electricity with the help of a generator. The most common type has horizonal axis and three blades, see Fisher (1990). The energy producing potential is very sensitive to the wind quality of the site (i.e. speed and reliability). The best wind energy technology at the best sites is competitive with fossil fired power plants. Wind energy is likely to be more area-intensive than solar energy, but the land between the turbines can be used for growing crops and cattle grazing. Wind energy sites influence the landscape aesthetics and some noise is generated, see Stevenson (1993). A small impact on the local ecosystem, in particular birds, can be expected.

3.8 Photovoltaics, solar thermal and solar heating

Sunlight is directly converted to electricity by photovoltaic cells. The cells are made of a thin semiconductor material (mostly silicon) doped with a specific amount of impurities. This technology has developed substantially in later years in terms of cost reduction and solar energy conversion efficiency, and future prospects are even better (WRI (1990)). The best photovoltaic cells are able to convert 14% of the solar energy to electricity under field conditions, confer Fisher (1990). Photovoltaics are employed in small scale in various consumer products, such as calculators and garden lighting, and also for lighting and charging systems for cottages and boats.

Large scale power stations require large areas and cause some environmental impacts. However, at 14% efficiency and a 25% capacity factor only 0.38% of the land area of the U.S. is required to supply the entire electricity load of the U.S. (Fisher (1990)). There are some toxic materials involved in manufacturing of photovoltaic cells which may be a health hazard for workers.

Solar thermal technologies can be employed in large scale to capture solar energy as heat or to produce steam for electricity generation. Parabolic dishes, parabolic troughs or flat mirrors employ tracking systems to focus the light on a receiver. The thermal efficiency can be up to 75%, whereas the electricity generation efficiency is up to 32% (Fisher (1990)). Solar thermal plants require some land and have some visual impact on the landscape. If solar collectors are overheated they may release toxic and corrosive gases.

A solar technology suitable in smaller scale is solar space heating of buildings and solar water heating. Passive systems use only convective forces generated by temperature differences to transport the heat transfer fluid, which is commonly water or air. In an active system the fluid is moved by a pump or fan. The solar energy is trapped as heat in flat plate collectors containing a black absorber, or through concentrating parabolic troughs or dishes. Solar technologies are also available for space cooling. An alternative technology is solar ponds, where solar energy is collected by water or another fluid and stored in a mass of the same fluid. Passive solar heating systems are often cost effective, especially if they are integrated in new buildings. The environmental impacts of decentralized solar heating is small, but there is a potential risk from leakage of toxic heat transfer fluids to domestic water supply (Fisher (1990)).

3.9 Biomass

Biomass energy is derived from vegetation or animal wastes. Fuelwood combustion is the simplest and most common thermochemical process for producing energy from biomass. Animal wastes and crop residues can be directly combusted or used for gas production. Another biomass energy source is municipal solid waste. Energy crops such as sugar cane, oil palm and fast-growing tree plantations can be converted to fuels like ethanol, methanol and various oils. Furthermore peat resources can be dried and burned. During biomass combustion carbon dioxide is released to the atmosphere. If the biomass stock is kept constant through reforestation etc. and the soil is not eroded, the same volume of carbon dioxide is sequestered in the new biomass. The environmental impacts of large-scale peat extraction are significant since the vegetation has to be stripped to remove the peat layer and the regeneration time is many hundred years. An advantage of using animal waste and municipal solid waste for combustion or as a gas resource is reduced emissions of the greenhouse gas methane. Other pollutants released to the atmosphere are particulates (i.a. polycyclic organic matter), nitrogen oxides, PAH and other hydrocarbons, and carbon monoxide (Argonne National Laboratory (1990)). Uncontrolled residual emissions may reduce ambient air quality in local communities and be a public health hazard. Wood-burning stoves employing newer technologies are available that reduce fuel consumption and release of air pollutants.

3.10 Geothermal energy

Geothermal energy is based on the heat which is contained within the crust of the earth. This heat is generated from nuclear fusion processes under very high pressures and temperatures at the center of the earth. At suitable sites (of high geothermal gradient) wells are drilled into a hot formation and heat extracted in the form of steam and/or hot water, which is employed to drive an electricity generator, see DiPippo (1991). Hot dry rock is a less mature technology with large potential, where heat is extracted from unusually hot regions of the earth's crust by way of drilling two wells and pumping water through, confer Brown, Potter and Myers (1991). At some sites hot water at lower temperatures is available close to the surface for district heating and heating of greenhouses (Thurston (1993)). The environmental impacts from geothermal energy systems are relatively small. Some carbon dioxide, hydrogen sulfide and mercury is released from the geofluid if it is not reinjected into the reservoir. Release of toxic brine (i.e. geothermal fluid) can pose a threat to local vegetation and groundwater. The land requirements and visual impact on the landscape of geothermal plants are less than for competing power plants (DiPippo (1991)). Some cases of land subsidence due to loss of geothermal pressure have been reported.

3.11 Tidal power

In tidal power plants the gravitational energy from the attraction of the sun and moon on the oceans is exploited. Huge masses of water are moved as a result of the Earth's axial rotation and the gravitational forces. Towards the coast at some locations the tidal difference can be greater than 6 meters due to shelving of the sea-bed and the funnelling of estuaries, see Carter (1993). The flooding tide is allowed to fill a basin naturally, after which the water is trapped behind a dam and released through turbines to generate electricity when the water ebbs away. Potential sites for tidal power plants are restricted due to the distribution of tide; in Europe to the UK and France, and to the Bay of Fundy in Canada. There may be some minor environmental impact from tidal power on fish and other marine life since coastal currents are affected.

4. Classification of environmental impacts

Environmental impacts may be classified according to geographical scale. At the local scale there are emissions of gases and particulate matter to air (atmosphere), release of pollutants to water (hydrosphere), and waste deposits (lithosphere). Furthermore there can be environmental impacts form excessive use of water (e.g. in geothermal power plants) and geologic impacts (such as land subsidence due to underground extraction of fossil fuels). At the regional scale (up to a few hundred kilometers) to the continental scale (up to two or three thousand kilometers) the air and water quality may be affected through emissions of gases and particulate matter, in particular through acid deposits. Finally, at the global scale the atmosphere may be affected through the release of greenhouse gases causing global warming and stratospheric ozone depletion. We emphasize emissions to the atmosphere since these are considered to cause the most serious environmental impacts from extraction, conversion, distribution and consumption of energy.

4.1 Local impacts

Several of the gases released to the atmosphere from energy conversion and consumption activities may have detrimental health effects on the population. Sulfur oxides, nitrogen oxides, carbon monoxide and particulates may induce pulmonary diseases such as asthma and allergies. Polynuclear aromatic hydrocarbons and other hydrocarbons are suspected to be carcinogens. Photochemical smog is generated by solar radiation acting on nitrogen oxides and hydrocarbons (from vehicle exhaust) in urban areas and contain reactive gases (like ozone) causing eye irritation and impaired lung function.

Sulfur oxides, nitrogen oxides and photochemical smog have negative impacts on vegetation and crops. These antrophogenic emissions is probably one of the factors that can explain the damage to forest areas in Central Europe first detected in the 1980s (Pleym et al. (1992)).

The local and regional climate (and possibly global climate) is influenced by thermal pollution from power plants and urban-industrial areas, and through changes in the characteristics of the land (and ocean) surface, confer Jäger (1983). One example of the latter could be large-scale development of solar thermal plants. Thermal pollution is related to energy conversion and use releasing heat, for example through cooling systems which is a part of power plants. The most well-known example is "urban heat islands". Such climate changes will influence local ecosystems.

Facilities for extraction, production, conversion and distribution of energy have some physical impact on the landscape. These facilities occupy land and the aesthetic value may be reduced due to mines, power plants, water reservoirs and power lines.

4.2 Acid deposits

Emissions of sulfur oxides and nitrogen oxides (and probably some particulates) can cause acidification of lakes and soil from a local to regional scale. The acid deposits place severe stress on many ecosystems, both fauna, soil and vegetation. Well-known examples are the reduced size and diversity of fish populations in Scandinavian lakes, the northeastern U.S. and southeastern Canada (Graedel and Crutzen (1989)).

An additional damage from acid deposits is corrosion of outdoor equipment, buildings and works of art. Photochemical smog has a corrosive effect on rubber and plastics, as well as a deleterious effect on human health.

4.3 Climate change

Carbon dioxide is responsible for about half of the global warming potential of all greenhouse gases in the atmosphere. The main source is combustion of fossil fuels. An additional source is emissions due to deforestation and reduced biomass stock, partly caused by biomass fuel combustion (such as firewood) and inadequate reforestation. There is also some warming contribution from nitrous oxide, where one of the sources is combustion of fossil fuels. Houghton et al. (1990) and (1992) present model estimates showing an increase in global average temperature from

2.2 °C to 4.8 °C from preindustrial time (taken to be 1765) to year 2070, with a best estimate of 3.3 °C. A global warming at this scale could have large consequences for natural ecosystems and human activities. There are, however, considerable uncertainties with respect to the speed and scale of regional warming, and to the geologic (i.a. Antarctic ice cap melting and sea level rise), environmental and economic consequences. One important feature is the speed of warming since plants and animals have some ability to adapt to a changing climate as long as the rate of change is not too high.

Sulfur particulates from coal and oil combustion are likely to have a cooling influence on the Northern Hemisphere since they reflect solar radiation and may affect the optical properties of clouds, and may thus have held global warming down somewhat (Houghton et al. (1992)).

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6 April 1995

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